The Breakthrough Listen *Exotica Catalog*:
Full notes on the *Exotica Catalog* entries

These are the notes for version **20E** of the Breakthrough Listen *Exotica Catalog*.

Like the *Exotica Catalog* itself, the notes are divided into the Prototype, Superlative, Anomaly (Non-SETI), Anomaly (SETI), and Control samples. The entries are organized as they are listed in Tables A1, B1, C1, C2, and D1 of the *Exotica Catalog* paper. The entries give the name of each object, with its unique ID in version 20E of the Catalog in brackets.

1. Prototypes

Explicit prototypes are those objects referred to as a "prototype", "archetype", "benchmark", "standard" object, "textbook example", or something similar that indicates they should be taken as the representative instance of the phenomenon. Implicit prototypes are objects where the language in a reference clearly indicates it is being taken as representative or famous without using such specific language. Examples of implicit prototypes include 349 Dembowska ("the only known asteroid" in the R class in Tholen 1984), T Pyx ("the Galaxy's most famous recurrent nova" in Patterson et al. 2017), Cyg OB2 ("an obvious choice" for examining OB stars in associations in Massey & Thompson (1991)), and Stephan's Quintet ("the poster child" for compact galaxy groups in Duc et al. 2018), as well as the examples listed for asteroid spectral classes in Bus & Binzel (2002) and galaxy morphologies in Buta et al. (2015).

1.1 Minor bodies

A phylum including minor planets, comets, small interstellar objects, and debris as found in protoplanetary disks and planetary rings.

Objects in this phylum are small, solid bodies, usually irregular in shape. As per the IAU definition of major and dwarf planets, they are generally not in hydrostatic equilibrium, although the "egg satellites" like Methone are an exception. Their geology is shaped mainly by cratering by external objects, although early in their history, ^{26}Al decay led to differentiation in these objects or their parent bodies.

Arguably, the phylum could be split into two between those objects large enough to be mainly held together by gravity and even smaller bodies like meteoroids.

We classify Solar System minor bodies according to both orbital family and composition, with a small number of additional subtypes. Minor bodies of specific compositions might be selected by ETIs for mining (c.f., Papagiannis 1978). From a SETI perspective, orbital families might be targeted by ETI probes to provide a unique vantage point over bodies like the Earth, or because they are dynamically stable for long periods of time and could accumulate a large number of artifacts (e.g., Benford 2019). There is a large overlap in some cases between spectral and orbital groups (as in DeMeo & Carry 2014), as with the E-belt and E-type asteroids, for which we use the same Prototype.

1.1.1 Asteroids

Mostly rock-dominated bodies found predominantly within inner Solar System. Most do not display cometary activity. By convention, their diameter is more than 1 meter.

1.1.1.1 Spectral types

For asteroids, our spectral-type system is largely taken from Tholen (1984) (see also Tedesco et al. 1989). We selected those types considered the most significant by Tholen (1984), adding those unique to one or a few members. Some intermediate classes that blend into larger "complexes" in the more recent Bus & Binzel (2002) taxonomy were omitted. In choosing the Prototypes, we were guided by the classifications of Tholen (1984), Tedesco et al. (1989), and Bus & Binzel (2002).

Abbreviations for frequently consulted references: T84: Tholen (1984); T89: Tedesco et al. (1989); B02: Bus & Binzel (2002)

A-type: 446 Aeternitas [001]

Type description: High albedo and red; olivine-like spectrum; rare; one of T84's "well-defined" classes (p. 136); edge class in B02 S-complex

446 Aeternitas *is Solar System source*

Reason for selection of 446 Aeternitas: Bigger of two in T89; consistent classification in T84, T89, B02
Relationships between 446 Aeternitas and other Exotica Catalog objects: Orbital primary: Sun [150]

Alternative prototype(s): 863 Benkoela: consistent classification in T84, T89, B02, presented as example A-type in B02 – smaller

C-type: 52 Europa [002]

Type description: Dark, neutral color; carbonaceous (surfaces covered with carbon compounds); large class; C complex in B02
Caveats about type: Stands in for several related carbonaceous spectral types in this work, like B
Type references: Chapman et al. (1975)

52 Europa *is Solar System source*
Reason for selection of 52 Europa: Biggest C-type that is unambiguously not dwarf planet; example (implicit prototype) in B02 Table 2
Notes on 52 Europa: Spectral classification: CF (T84), C (T89), C (B02)
Works where 52 Europa referred to as prototype: Bus & Binzel (2002)
Relationships between 52 Europa and other Exotica Catalog objects: Orbital primary: Sun [150]

Alternative prototype(s): 10 Hygiea: larger C-type, possible dwarf planet (Vernazza et al. 2020)

D-type: 624 Hektor [003]

Type description: Dark, red; typical spectral type for large Jupiter Trojans (DeMeo & Carry 2014); one of T84's well-defined classes (p. 136); independent class in B02

624 Hektor *is Solar System source*
Reason for selection of 624 Hektor: Largest D-type; elsewhere in catalog
Notes on 624 Hektor: Not in T89 or B02
General works about 624 Hektor: Marchis et al. (2014)
Relationships between 624 Hektor and other Exotica Catalog objects: Orbital primary: Sun [150]

E-type: 434 Hungaria [004]

Type description: Very high albedo, M-type like colors; most commonly found in Hungaria family; one of T84's well-defined classes (p. 136); Xe type in B02

434 Hungaria *is Solar System source*
Reason for selection of 434 Hungaria: Elsewhere in catalog; one example (implicit prototype) presented in B02 for Xe
Works where 434 Hungaria referred to as prototype: Bus & Binzel (2002)
Relationships between 434 Hungaria and other Exotica Catalog objects: Orbital primary: Sun [150]

Alternative prototype(s): 64 Angelina: bigger, explicit prototype in B02 – in main belt instead of Hungaria family

M-type: 16 Psyche [005]

Type description: Metallic asteroid; one of T84's well-defined classes (p. 136); mostly split among X complex subclasses in B02
Type references: Rivkin et al. (2000)

16 Psyche *is Solar System source*
Reason for selection of 16 Psyche: Largest M-type
Notes on 16 Psyche: Target of planned *Psyche* mission; possibly former core of differentiated planetesimal, alternatively may be related to enstatite chondrites; spectral classification: M (T84), M (T89), X (B02)
General works about 16 Psyche: Shepard et al. (2017)
Relationships between 16 Psyche and other Exotica Catalog objects: Orbital primary: Sun [150]

O-type: 3628 Božněmcová [006]

Type description: Composition like ordinary chondritic meteorites; very rare; independent class in B02

3628 Božněmcová *is Solar System source*
Reason for selection of 3628 Božněmcová: Implicit prototype: example in B02 Table 2
Works where 3628 Božněmcová referred to as prototype: Bus & Binzel (2002)
Relationships between 3628 Božněmcová and other Exotica Catalog objects: Orbital primary: Sun [150]

P-type: 420 Bertholda [007]

Type description: Dark, red; between C- and D-type; common in Cybele and Hilda families and Jupiter Trojans (DeMeo & Carry 2014), one of T84's well-defined classes (p. 136); undefined in B02, subsumed into X complex

420 Bertholda *is Solar System source*
Reason for selection of 420 Bertholda: Largest P-type in T89, T84
Notes on 420 Bertholda: Not classified in B02
Relationships between 420 Bertholda and other Exotica Catalog objects: Orbital primary: Sun [150]

Q-type: 1862 Apollo [008]

Type description: Unique classification for 1862 Apollo in T84; edge class in B02 S-complex; found among near-Earth asteroids

1862 Apollo *is Solar System source*
Reason for selection of 1862 Apollo: Prototype by uniqueness in T84; example (implicit prototype) in B02 Table 2; elsewhere in catalog
Works where 1862 Apollo referred to as prototype: Tholen (1984); Bus & Binzel (2002)
Relationships between 1862 Apollo and other Exotica Catalog objects: Orbital primary: Sun [150]

R-type: 349 Dembowska [009]

Type description: Unique classification for 349 Dembowska in T84; edge class in B02 S-complex

349 Dembowska *is Solar System source*
Reason for selection of 349 Dembowska: Prototype by uniqueness in T84; explicit prototype in B02 and example in Table 2
Notes on 349 Dembowska: Spectral classification: R (T84), r (T89), R (B02)
Works where 349 Dembowska referred to as prototype: Tholen (1984); Bus & Binzel (2002)
Relationships between 349 Dembowska and other Exotica Catalog objects: Orbital primary: Sun [150]

S-type: 15 Eunomia [010]

Type description: Moderately bright, reddish in visible light; stony; large class; abundant in inner and middle asteroid belt; S complex in B02
Caveats about type: Stands in for several fine classes in B02

15 Eunomia *is Solar System source*
Reason for selection of 15 Eunomia: Biggest example; consistent classification in T84, T89, B02
Relationships between 15 Eunomia and other Exotica Catalog objects: Orbital primary: Sun [150]

T-type: 233 Asterope [011]

Type description: Properties between D and P class, albedo and color combination rare
Caveats about type: Limited overlap between T-type asteroids in T84 and B02

233 Asterope *is Solar System source*
Reason for selection of 233 Asterope: Biggest example (in T84 and T89)
Notes on 233 Asterope: Spectral classification: T (T84, T89), K (B02)
Relationships between 233 Asterope and other Exotica Catalog objects: Orbital primary: Sun [150]

Alternative prototype(s): 308 Polyxo: only asteroid that is T-type in both T84 and B02 – l-type in T89

V-type: 4 Vesta [012]

Type description: Composition similar to basaltic achondrite HED meteroites; associated with Vesta family asteroids; unique classification for 4 Vesta in T84; independent class in B02

4 Vesta *is Solar System source*
Reason for selection of 4 Vesta: Prototype by uniqueness in T84; example in B02 Table 2
Caveats about selection of 4 Vesta: Considered to be protoplanet – generally not classed as dwarf planet (c.f., Vernazza et al. 2020)
Notes on 4 Vesta: Studied intensively by *Dawn*
Works where 4 Vesta referred to as prototype: Tholen (1984); Bus & Binzel (2002)
General works about 4 Vesta: Russell et al. (2012)
Relationships between 4 Vesta and other Exotica Catalog objects: Orbital primary: Sun [150]

1.1.1.2 Multiple asteroids

Binary (double) asteroid: 90 Antiope [013]

Type description: Two asteroids in close orbit around each other, sizes are comparable to order of magnitude
Type references: Richardson & Walsh (2006)

90 Antiope *is Solar System source*
Reason for selection of 90 Antiope: One of first discovered; components nearly same size
Works relating 90 Antiope to type: Descamps et al. (2007)
Relationships between 90 Antiope and other Exotica Catalog objects: Orbital primary: Sun [150]

Asteroid moon: Dactyl [014]

Type description: Asteroid body in orbit around much larger asteroid

Dactyl *is Solar System source*
Dactyl also known as: 243 Ida I Dactyl
Reason for selection of Dactyl: First certain discovery; encountered by *Galileo*
Notes on Dactyl: Parent body is 243 Ida; orbit around Ida is poorly constrained – given values of 90 km refer to the distance between Ida and Dactyl during the *Galileo* encounter.
Works relating Dactyl to type: Chapman et al. (1995); Belton et al. (1996)

1.1.1.3 Orbital classification

Asteroids grouped by orbital characteristics, including planetary orbits crossed and groupings in semimajor axis, eccentricity, and inclination. Includes but is not limited to asteroid families resulting from destruction of progenitor family.

Mercury-crossers: 3200 Phaethon [015]

Type description: Perihelion of asteroid inside Earth orbit, although aphelion is usually outside Earth orbit

3200 Phaethon *is Solar System source*
Reason for selection of 3200 Phaethon: Largest example, well-studied
Caveats about selection of 3200 Phaethon: Shows comet-like activity, possible "rock comet"
Notes on 3200 Phaethon: Planned target of DESTINY+; is also an Apollo-type asteroid
General works about 3200 Phaethon: Jewitt & Li (2010)
Relationships between 3200 Phaethon and other Exotica Catalog objects: Orbital primary: Sun [150]

Vatira: 2020 AV_2 [016]

Type description: Orbit entirely within Venus' orbit; $Q < 0.718$ AU

2020 AV_2 *is Solar System source*
Reason for selection of 2020 AV_2: Only known example
Works relating 2020 AV_2 to type: Greenstreet (2020)
General works about 2020 AV_2: de la Fuente Marcos & de la Fuente Marcos (2020a); Jet Propulsion Laboratory (2020a);

Greenstreet (2020)
Relationships between 2020 AV_2 and other Exotica Catalog objects: Orbital primary: Sun [150]

Venus co-orbital: (322756) 2001 CK_{32} [017]

Type description: Asteroid that is on Trojan, quasisatellite, or horseshoe solar orbit with Venus
Type references: de la Fuente Marcos & de la Fuente Marcos (2014)

(322756) 2001 CK_{32} *is Solar System source*
Reason for selection of (322756) 2001 CK_{32}: Brightest in absolute magnitude
Works relating (322756) 2001 CK_{32} to type: de la Fuente Marcos & de la Fuente Marcos (2014)
Relationships between (322756) 2001 CK_{32} and other Exotica Catalog objects: Orbital primary: Sun [150]

Atira: 163693 Atira [018]

Type also known as: Interior Earth Object (IEO); Apohele
Type description: Orbit entirely within Earth's orbit; $Q < 0.983$ AU (Earth perihelion)
Type references: Greenstreet et al. (2012)

163693 Atira *is Solar System source*
Reason for selection of 163693 Atira: Eponym; observed with radar
Relationships between 163693 Atira and other Exotica Catalog objects: Orbital primary: Sun [150]

Aten: 3753 Cruithne [019]

Type description: Earth-crossing orbit; $q < a < 1.0$ AU, $Q > 0.983$ AU

3753 Cruithne *is Solar System source*
Reason for selection of 3753 Cruithne: Well-known; elsewhere in catalog
Caveats about selection of 3753 Cruithne: Is Earth co-orbital, unlike typical Atens
General works about 3753 Cruithne: Wiegert et al. (1997)
Relationships between 3753 Cruithne and other Exotica Catalog objects: Orbital primary: Sun [150]

Arjuna: 1991 VG [020]

Type description: Very nearly Earth-like orbit with low eccentricity and inclination (0.985 AU $< a <$ 1.013 AU; $e < 0.1$; $i < 8.56$ deg)
Caveats about type: Not officially designated as class
Type references: de la Fuente Marcos & de la Fuente Marcos (2015)

1991 VG *is Solar System source*
Reason for selection of 1991 VG: First discovered; SETI historical context; possible target of *NEA Scout*
Caveats about selection of 1991 VG: No longer fits de la Fuente Marcos & de la Fuente Marcos (2015) definition of Arjuna orbit; has been suspected to be anthropogenic space debris in the past although now believed to be natural
Notes on 1991 VG: Formerly a temporary satellite of Earth
General works about 1991 VG: de la Fuente Marcos & de la Fuente Marcos (2018)
Relationships between 1991 VG and other Exotica Catalog objects: Orbital primary: Sun [150]

Relationship to SETI: 1991 VG proposed by Steel (1995) to be ETI probe

Apollo: 1862 Apollo [008]

Type description: Earth-crossing orbit; $q < 1.017$ AU (Earth aphelion), $a > 1.0$ AU

1862 Apollo *is Solar System source*
Reason for selection of 1862 Apollo: Eponym; elsewhere in catalog
General works about 1862 Apollo: Bus & Binzel (2002); Tholen (1984)
Relationships between 1862 Apollo and other Exotica Catalog objects: Orbital primary: Sun [150]

Earth Trojan: 2010 TK_7 [021]

Type also known as: Earth tadpole orbit
Type description: Asteroid confined near Earth-Sun Lagrange point L_4 or L_5; in geocentric frame, appears to orbit L_4 or L_5; orbits Sun; Earth co-orbital; potentially very stable
Type references: Brasser et al. (2004)

2010 TK$_7$ *is Solar System source*
Reason for selection of 2010 TK$_7$: Only known example
Notes on 2010 TK$_7$: Located around Earth-Sun L_4 (leading)
Works relating 2010 TK$_7$ to type: Connors et al. (2011)
Relationships between 2010 TK$_7$ and other Exotica Catalog objects: Orbital primary: Sun [150]

Relationship to SETI: Earth co-orbitals proposed as locations of ETI Earth-observing probe in Benford (2019)

Earth horseshoe orbit: 3753 Cruithne [019]

Type description: In geocentric frame, the asteroid appears to wander from leading Earth past the far side of Earth's orbit beyond the Sun to trailing the Earth and back; in simplest case, has a horseshoe shape looping around the stable Earth-Sun Lagrange points L_4 and L_5 and the unstable point L3, but does not contain the Earth or Sun; actually orbits Sun; Earth co-orbital
Type references: Brasser et al. (2004)

3753 Cruithne *is Solar System source*
Reason for selection of 3753 Cruithne: First known example; most famous; elsewhere in catalog
Works relating 3753 Cruithne to type: Wiegert et al. (1997)
Relationships between 3753 Cruithne and other Exotica Catalog objects: Orbital primary: Sun [150]

Relationship to SETI: Earth co-orbitals proposed as locations of ETI Earth-observing probe in Benford (2019)

Earth quasisatellite: (469219) Kamo'oalewa [022]

Type description: In geocentric frame, appears to orbit Earth but not Sun; actually orbits Sun (outside of Earth's Hill sphere); Earth co-orbital
Type references: Brasser et al. (2004)

(469219) Kamo'oalewa *is Solar System source*
Reason for selection of (469219) Kamo'oalewa: Closest, most stable
Works relating (469219) Kamo'oalewa to type: de la Fuente Marcos & de la Fuente Marcos (2016)
Relationships between (469219) Kamo'oalewa and other Exotica Catalog objects: Orbital primary: Sun [150]

Relationship to SETI: Earth co-orbitals proposed as locations of ETI Earth-observing probe in Benford (2019)

Earth Kozai librator: 4660 Nereus [023]

Type description: Earth-crossing orbit, but never approaches closely because of Kozai resonance with Earth; very stable over 0.1–1 Myr
Type references: Michel & Thomas (1996)

4660 Nereus *is Solar System source*
Reason for selection of 4660 Nereus: First identified example
Works relating 4660 Nereus to type: Michel & Thomas (1996)
Relationships between 4660 Nereus and other Exotica Catalog objects: Orbital primary: Sun [150]

Relationship to SETI: Relatively stable near-Earth orbit for ETI probe?

Amor: 433 Eros [024]

Type description: Near-Earth asteroid but not Earth-crossing orbit; $1.017 \text{ AU} < q < 1.3 \text{ AU}$ (Greenstreet et al. 2012)

433 Eros *is Solar System source*
Reason for selection of 433 Eros: Extremely well studied; second biggest

Notes on 433 Eros: Orbited and landed upon by NEAR-Shoemaker
General works about 433 Eros: Robinson et al. (2002)
Relationships between 433 Eros and other Exotica Catalog objects: Orbital primary: Sun [150]

Mars Trojan: 5261 Eureka [025]

Type description: Mars co-orbital asteroid; confined to Mars-Sun L_4 or L_5 points
Type references: Scholl et al. (2005); Polishook et al. (2017)

5261 Eureka *is Solar System source*
Reason for selection of 5261 Eureka: First discovered
Notes on 5261 Eureka: Possibly Mars impact ejecta (Polishook et al. 2017)
Works relating 5261 Eureka to type: Mikkola et al. (1994)
Relationships between 5261 Eureka and other Exotica Catalog objects: Orbital primary: Sun [150]

Hungaria: 434 Hungaria [004]

Type description: Outside Mars orbit but quite far interior to main asteroid belt; 1.8 AU $\lesssim a \lesssim$ 2.0 AU at high inclination; Bottke et al. (2012) speculates Hungarias are survivors of now depopulated inner asteroid belt from early in the Solar System (E-belt)

434 Hungaria *is Solar System source*
Reason for selection of 434 Hungaria: Eponym; elsewhere in catalog
General works about 434 Hungaria: Bus & Binzel (2002)
Relationships between 434 Hungaria and other Exotica Catalog objects: Orbital primary: Sun [150]

Flora family asteroid: 8 Flora [026]

Type description: Collisional family of asteroids in inner belt; unusually high inclination (~ 30 deg)

8 Flora *is Solar System source*
Reason for selection of 8 Flora: Eponym; largest
Relationships between 8 Flora and other Exotica Catalog objects: Orbital primary: Sun [150]

Main Belt Zone I: 4 Vesta [012]

Type description: "Inner" asteroid belt; one of three zones containing bulk of asteroids; between 4:1 and 3:1 Jupiter resonances

4 Vesta *is Solar System source*
Reason for selection of 4 Vesta: Largest example; well-studied by *Dawn*; elsewhere in catalog
Caveats about selection of 4 Vesta: Considered to be protoplanet – generally not classed as dwarf planet (c.f., Vernazza et al. 2020)
General works about 4 Vesta: Bus & Binzel (2002); Tholen (1984); Russell et al. (2012)
Relationships between 4 Vesta and other Exotica Catalog objects: Orbital primary: Sun [150]

Phocaea family asteroid: 25 Phocaea [027]

Type description: Collisional family of asteroids

25 Phocaea *is Solar System source*
Reason for selection of 25 Phocaea: Eponym
Relationships between 25 Phocaea and other Exotica Catalog objects: Orbital primary: Sun [150]

Main Belt Zone II: 15 Eunomia [010]

Type description: "Middle" asteroid belt; one of three zones containing bulk of asteroids; between 3:1 and 5:2 Jupiter resonances

15 Eunomia *is Solar System source*

Reason for selection of 15 Eunomia: Large example; not dwarf planet
Relationships between 15 Eunomia and other Exotica Catalog objects: Orbital primary: Sun [150]

Main Belt Zone III: 52 Europa [002]

Type description: "Outer" asteroid belt; one of three zones containing bulk of asteroids; between 5:2 and 2:1 Jupiter resonances

52 Europa *is Solar System source*
Reason for selection of 52 Europa: Large example; not dwarf planet; elsewhere in catalog
General works about 52 Europa: Bus & Binzel (2002)
Relationships between 52 Europa and other Exotica Catalog objects: Orbital primary: Sun [150]

Cybele: 65 Cybele [028]

Type description: Outside three main zones of asteroid belt; between 2:1 and 5:3 Jupiter resonances
Type references: De Prá et al. (2018)

65 Cybele *is Solar System source*
Reason for selection of 65 Cybele: Eponym
Relationships between 65 Cybele and other Exotica Catalog objects: Orbital primary: Sun [150]

Hilda: 153 Hilda [029]

Type description: Far outside main belt, but interior to Jupiter; in 3:2 resonance with Jupiter
Type references: Grav et al. (2012); De Prá et al. (2018)

153 Hilda *is Solar System source*
Reason for selection of 153 Hilda: Eponym
Relationships between 153 Hilda and other Exotica Catalog objects: Orbital primary: Sun [150]

Jupiter Trojan: 624 Hektor [003]

Type description: Jupiter co-orbital asteroid; confined to Jupiter-Sun L_4 or L_5 points
Type references: Jewitt et al. (2000); Grav et al. (2011); Slyusarev & Belskaya (2014)

624 Hektor *is Solar System source*
Reason for selection of 624 Hektor: Well-studied; second discovered
Notes on 624 Hektor: Is a contact binary asteroid with a satellite; not target of planned *Lucy* mission
General works about 624 Hektor: Marchis et al. (2014)
Relationships between 624 Hektor and other Exotica Catalog objects: Orbital primary: Sun [150]

1.1.2 Comets

1.1.2.1 Compositional classification

Typical composition: 6P/d'Arrest [030]

Type description: Comet with normal abundances of carbon chain molecules (containing C_2 and C_3) relative to water
Type references: A'Hearn et al. (1995); Fink (2009); Cochran et al. (2012)

6P/d'Arrest *is Solar System source*
Reason for selection of 6P/d'Arrest: Listed as "typical" for all three of A'Hearn et al. (1995); Fink (2009); Cochran et al. (2012)
Works relating 6P/d'Arrest to type: A'Hearn et al. (1995); Fink (2009); Cochran et al. (2012)
Relationships between 6P/d'Arrest and other Exotica Catalog objects: Orbital primary: Sun [150]

Carbon-chain depleted comet: 21P/Giacobini-Zinner [031]

Type description: Comet with low abundance of carbon chain molecules (containing C_2 and C_3) relative to water, the

most numerous of comets with atypical composition
Type references: A'Hearn et al. (1995); Fink (2009); Cochran et al. (2012)

21P/Giacobini-Zinner *is Solar System source*
Reason for selection of 21P/Giacobini-Zinner: Explicit prototype; listed as depleted in A'Hearn et al. (1995); Cochran et al. (2012), C_2 depleted in Fink (2009)
Works where 21P/Giacobini-Zinner referred to as prototype: Cochran et al. (2015, 2020)
Works relating 21P/Giacobini-Zinner to type: Schleicher et al. (1987)
Relationships between 21P/Giacobini-Zinner and other Exotica Catalog objects: Orbital primary: Sun [150]

1.1.2.1.1 Activity level classification

Active comet: 1P/Halley [032]

Type description: Icy composition; volatiles near surface sublimate when close to Sun, resulting in minor body (nucleus) being surrounded by gas and dust envelope (coma), with tails of gas and dust pointing away from Sun
Type references: Keller & Kührt (2020)

1P/Halley *is Solar System source*
Reason for selection of 1P/Halley: First identified periodic comet, with well-known orbit and bounded distance from Earth; famous example; elsewhere in catalog
Notes on 1P/Halley: Visited by Halley Armada in 1986 approach, including close flyby by *Giotto*; next perihelion in 2061
Works relating 1P/Halley to type: Keller et al. (1986)
General works about 1P/Halley: Kissel et al. (1986); Krankowsky et al. (1986); Keller et al. (1986)
Relationships between 1P/Halley and other Exotica Catalog objects: Orbital primary: Sun [150]

Manx: C/2014 S3 (PAN-STARRS) [033]

Type description: Objects with cometary orbits (high e, high a) but asteroidal compositions; display little or no activity anytime during history, with no tails; formed in inner Solar System, now reside in Oort Cloud
Type references: Shannon et al. (2015); Meech et al. (2016)

C/2014 S3 (PAN-STARRS) *is Solar System source*
Reason for selection of C/2014 S3 (PAN-STARRS): Spectrum like definite asteroidal type (S-type)
Caveats about selection of C/2014 S3 (PAN-STARRS): Has displayed minor activity
Works relating C/2014 S3 (PAN-STARRS) to type: Meech et al. (2016)
Relationships between C/2014 S3 (PAN-STARRS) and other Exotica Catalog objects: Orbital primary: Sun [150]

Extinct: 5335 Damocles [034]

Type description: Formerly active comet, frequently still in cometary orbit; no accessible volatiles left to sublimate
Type references: Hartmann et al. (1987); Jewitt (2005)

5335 Damocles *is Solar System source*
Reason for selection of 5335 Damocles: Eponym for Damocloid class of extinct comets in Halley-type orbits; explict prototype
Works where 5335 Damocles referred to as prototype: Jewitt (2005)
Works relating 5335 Damocles to type: Asher et al. (1994)
Relationships between 5335 Damocles and other Exotica Catalog objects: Orbital primary: Sun [150]

1.1.2.2 Exocomets

Falling evaporating body: β Pic [035]

Abbreviations for type: FEB
Type description: Comets observed spectroscopically in transit around young A-type stars as variable absorption lines, occur in large numbers in these systems; believed to be kilometer size objects destroyed when coming within a few stellar radii
Type references: Vidal-Madjar et al. (1994); Beust et al. (2001)

β **Pic** *is sidereal source*
Reason for selection of β Pic: First identified; best studied; star elsewhere in catalog and in I17

Works relating β Pic to type: Artymowicz (1997); Kiefer et al. (2014)
β Pic in I17

1.1.2.3 Orbital classification

The comet orbital classifications were informed by Levison (1996).

Encke-type: 2P/Encke [036]

Type description: Aphelion interior to Jupiter, Tisserand $T > 3$ ($q < Q \lesssim 4$ AU in Horner et al. 2003); not in main asteroid belt
Type references: Levison & Duncan (1997); Horner et al. (2003)

2P/Encke *is Solar System source*
Reason for selection of 2P/Encke: Eponym; first known
Works relating 2P/Encke to type: Levison et al. (2006)
Relationships between 2P/Encke and other Exotica Catalog objects: Orbital primary: Sun [150]

Main belt comet: 133P/Elst-Pizarro [037]

Type description: Object orbits entirely within main asteroid belt, but displays cometary activity not due to collision
Type references: Jewitt (2012)

133P/Elst-Pizarro *is Solar System source*
133P/Elst-Pizarro also known as: 7968 Elst-Pizarro
Reason for selection of 133P/Elst-Pizarro: Explicit prototype; first discovered
Works where 133P/Elst-Pizarro referred to as prototype: Jewitt et al. (2009)
Works relating 133P/Elst-Pizarro to type: Hsieh et al. (2004)
Relationships between 133P/Elst-Pizarro and other Exotica Catalog objects: Orbital primary: Sun [150]

Jupiter-family comet: 9P/Tempel 1 [038]

Abbreviations for type: JFC
Type description: Jupiter-crossing orbit, Tisserand T in range 2–3; low speed encounters with Jupiter are possible allowing it to deflect orbit; periods $\lesssim 20$ yr
Type references: Levison (1996); Levison & Duncan (1997); Tancredi et al. (2006)

9P/Tempel 1 *is Solar System source*
Reason for selection of 9P/Tempel 1: Well-studied: visited by *Deep Impact* and *Stardust*
General works about 9P/Tempel 1: A'Hearn et al. (2005); Veverka et al. (2013)
Relationships between 9P/Tempel 1 and other Exotica Catalog objects: Orbital primary: Sun [150]

Chiron-type comet: 95P/Chiron [039]

Type description: Orbit exterior to Jupiter but generally interior to Neptune; Tisserand $T > 3$; display activity, including coma
Relationship with other types: Is active Centaur
Type references: Levison (1996); Jewitt (2009)

95P/Chiron *is Solar System source*
95P/Chiron also known as: 2060 Chiron
Reason for selection of 95P/Chiron: Explicit prototype and eponym
Works where 95P/Chiron referred to as prototype: Jewitt (2009)
Works relating 95P/Chiron to type: Hartmann et al. (1990)
General works about 95P/Chiron: Jewitt (2009); Jet Propulsion Laboratory (2020a); Ortiz et al. (2015); Hartmann et al. (1990)
Relationships between 2060 Chiron and other Exotica Catalog objects: Orbital primary: Sun [150]

Halley-type comet: 1P/Halley [032]

Type description: Jupiter-crossing orbit, Tisserand $T < 2$; periods between 20–200 yr
Type references: Levison (1996)

1P/Halley *is Solar System source*
Reason for selection of 1P/Halley: Eponym; first recognized; elsewhere in catalog
General works about 1P/Halley: Kissel et al. (1986); Krankowsky et al. (1986); Keller et al. (1986)
Relationships between 1P/Halley and other Exotica Catalog objects: Orbital primary: Sun [150]

Long-period comet: 153P/Ikeya-Zhang [040]

Type description: Orbital period more than 200 yr; usually but not always millennia, with aphelion in Oort Cloud

153P/Ikeya-Zhang *is Solar System source*
Reason for selection of 153P/Ikeya-Zhang: Established period with bounded distance from Earth
Works relating 153P/Ikeya-Zhang to type: Hasegawa & Nakano (2003)
Relationships between 153P/Ikeya-Zhang and other Exotica Catalog objects: Orbital primary: Sun [150]

1.1.3 Distant minor planets

'Distant minor planets", adapting the "distant objects" term used by the Minor Planet Center, refer to outer Solar System bodies beyond the Jupiter Trojans that are not comets. We aimed to select Prototypes that are almost certainly minor bodies and not dwarf planets, as indicated by a "probably not dwarf planet" designation on Mike Brown's website.

1.1.3.1 Color classification

The spectral type system is that of Barucci et al. (2005) and Fulchignoni et al. (2008), with the latter guiding our Prototype selection.

BB-type: (24835) 1995 SM_{55} [041]

Type description: Neutral color object
Type references: Barucci et al. (2005); Fulchignoni et al. (2008)

(24835) 1995 SM_{55} *is Solar System source*
Reason for selection of (24835) 1995 SM_{55}: Listed as BB in Fulchignoni et al. (2008) and Barucci et al. (2008); Brown (2020): "probably not" dwarf planet; elsewhere in catalog
Relationships between (24835) 1995 SM_{55} and other Exotica Catalog objects: Orbital primary: Sun [150]

BR-type: (15788) 1993 SB [042]

Type description: Intermediate (somewhat red) color object
Type references: Barucci et al. (2005); Fulchignoni et al. (2008)

(15788) 1993 SB *is Solar System source*
Reason for selection of (15788) 1993 SB: Listed as BB in Fulchignoni et al. (2008); Brown (2020): "probably not" dwarf planet
Relationships between (15788) 1993 SB and other Exotica Catalog objects: Orbital primary: Sun [150]

IR-type: (385185) 1993 RO [043]

Type description: Intermediate (red) color object
Type references: Barucci et al. (2005); Fulchignoni et al. (2008)

(385185) 1993 RO *is Solar System source*
Reason for selection of (385185) 1993 RO: Listed as IR in Fulchignoni et al. (2008); too small to be dwarf planet; elsewhere in catalog
Relationships between (385185) 1993 RO and other Exotica Catalog objects: Orbital primary: Sun [150]

RR-type: 15760 Albion [044]

Type description: Ultrared object
Type references: Mueller et al. (1992); Barucci et al. (2005); Fulchignoni et al. (2008)

15760 Albion *is Solar System source*
15760 Albion also known as: (15760) 1992 QB_1
Reason for selection of 15760 Albion: First minor KBO discovered and well-studied; listed as RR in Fulchignoni et al. (2008); Brown (2020): "probably not" dwarf planet; elsewhere in catalog
Relationships between 15760 Albion and other Exotica Catalog objects: Orbital primary: Sun [150]

Alternative prototype(s): 5145 Pholus: noted for red color, early Centaur discovery (Mueller et al. 1992)

1.1.3.2 Multiple icy bodies

Binary KBO: 79360 Sila-Nunam [045]

Type description: Two icy bodies in close orbit around each other, sizes may be nearly equal
Type references: Noll et al. (2008)

79360 Sila-Nunam *is Solar System source*
Reason for selection of 79360 Sila-Nunam: Components are very nearly same size (125 ± 15 km and 118 ± 14 km)
Works relating 79360 Sila-Nunam to type: Grundy et al. (2012)
Relationships between 79360 Sila-Nunam and other Exotica Catalog objects: Orbital primary: Sun [150]

1.1.3.3 Orbital classification

The division into orbital groups is based on the system in Gladman et al. (2008), which we consulted especially when selecting Scattered Disk and Detached objects.

Centaur: 2060 Chiron [039]

Type description: Orbit exterior to Jupiter but generally interior to Neptune; dynamical lifetime of a few Myr
Type references: Horner et al. (2004); Jewitt (2009)

2060 Chiron *is Solar System source*
Reason for selection of 2060 Chiron: Explicit prototype; famous, well-studied; elsewhere in catalog
Works where 2060 Chiron referred to as prototype: Jewitt (2009)
General works about 2060 Chiron: Jewitt (2009); Jet Propulsion Laboratory (2020a); Ortiz et al. (2015); Hartmann et al. (1990)
Relationships between 2060 Chiron and other Exotica Catalog objects: Orbital primary: Sun [150]

Uranus Trojan: 2011 QF_{99} [046]

Type description: Uranus co-orbital object; confined to Uranus-Sun L_4 or L_5 points; very rare
Type references: Nesvorný & Dones (2002); Zhou et al. (2020)

2011 QF_{99} *is Solar System source*
Reason for selection of 2011 QF_{99}: First discovered example
Works relating 2011 QF_{99} to type: Alexandersen et al. (2013)
Relationships between 2011 QF_{99} and other Exotica Catalog objects: Orbital primary: Sun [150]

Neptune Trojan: 2001 QR_{322} [047]

Type description: Neptune co-orbital object; confined to Neptune-Sun L_4 or L_5 points; relatively common and potentially stable orbits
Type references: Sheppard & Trujillo (2006, 2010a,b)

2001 QR_{322} *is Solar System source*
Reason for selection of 2001 QR_{322}: First recognized example, although smaller than 2006 RJ103
Relationships between 2001 QR_{322} and other Exotica Catalog objects: Orbital primary: Sun [150]

Plutino: (385185) 1993 RO [043]

Type description: Resonant Kuiper Belt Object in 3:2 resonance with Neptune; semimajor axis interior to bulk of Kuiper Belt

Type references: Gladman et al. (2012)

(385185) 1993 RO *is Solar System source*

Reason for selection of (385185) 1993 RO: Second discovered; too small to be dwarf planet

Relationships between (385185) 1993 RO and other Exotica Catalog objects: Orbital primary: Sun [150]

Cold classical Kuiper Belt Object: 15760 Albion [044]

Type also known as: Cold cubewano

Type description: Low to moderate eccentricity, low inclination ($i \lesssim 5$ deg) Kuiper Belt object not in resonance with Neptune; 39.4 AU $< a <$ 48.2 AU; "cold" refers to orbital dynamics, not physical temperature

Type references: Levison & Stern (2001); Gladman et al. (2008); Vilenius et al. (2014); Stern et al. (2019)

15760 Albion *is Solar System source*

15760 Albion also known as: (15760) 1992 QB_1

Reason for selection of 15760 Albion: First discovered KBO; Brown (2020): "probably not" dwarf planet

Relationships between 15760 Albion and other Exotica Catalog objects: Orbital primary: Sun [150]

Alternative prototype(s): 486958 Arrokoth: studied in flyby by *New Horizons*

Hot classical Kuiper Belt Object: (523899) 1997 CV_{29} [048]

Type also known as: Hot cubewano

Type description: Low to moderate eccentricity, moderate inclination Kuiper Belt object not in resonace with Neptune; 39.4 AU $< a <$ 48.2 AU; "hot" refers to orbital dynamics, not physical temperature

Type references: Levison & Stern (2001); Gladman et al. (2008); Vilenius et al. (2014)

(523899) 1997 CV_{29} *is Solar System source*

Reason for selection of (523899) 1997 CV_{29}: Early discovery; Brown (2020): "probably not" dwarf planet

Relationships between (523899) 1997 CV_{29} and other Exotica Catalog objects: Orbital primary: Sun [150]

Haumea family object: (24835) 1995 SM_{55} [041]

Type description: Member of family with dwarf planet Haumea; origin of family unclear

Type references: Brown et al. (2007); Schlichting & Sari (2009); Pike et al. (2020)

(24835) 1995 SM_{55} *is Solar System source*

Reason for selection of (24835) 1995 SM_{55}: First discovered; Brown (2020): "probably not" dwarf planet

Relationships between (24835) 1995 SM_{55} and other Exotica Catalog objects: Orbital primary: Sun [150]

Twotino: (20161) 1996 TR_{66} [049]

Type description: Resonant Kuiper Belt Object in 2:1 resonance with Neptune; semimajor axis outside bulk of Kuiper Belt

Type references: Gladman et al. (2012)

(20161) 1996 TR_{66} *is Solar System source*

Reason for selection of (20161) 1996 TR_{66}: First discovered; Brown (2020): "probably not" dwarf planet

Relationships between (20161) 1996 TR_{66} and other Exotica Catalog objects: Orbital primary: Sun [150]

Scattered Disk Object: (91554) 1999 RZ_{215} [050]

Abbreviations for type: SDO

Type description: Orbit mostly exterior to Neptune but with perihelion near Neptune's orbit; high eccentricity, inclination, or semimajor axis

Type references: Gladman et al. (2008)

(91554) 1999 RZ_{215} *is Solar System source*

Reason for selection of (91554) 1999 RZ_{215}: Given in Gladman et al. (2008), only numbered example with q greater than Neptune perihelion; Brown (2020): "probably not" dwarf planet
Relationships between (91554) 1999 RZ_{215} and other Exotica Catalog objects: Orbital primary: Sun [150]

Detached object: (181902) 1999 RD_{215} [051]

Type also known as: Extended Scattered Disk Object (ESDO); Extended Disk Object (EDO)
Type description: Minor body with orbit entirely exterior to Neptune; large semimajor axis (outside 2:1 resonance with Neptune) and generally large eccentricity (Gladman et al. 2008: $e > 0.24$)
Type references: Gladman et al. (2002, 2008); Santos-Sanz et al. (2012)

(181902) 1999 RD_{215} *is Solar System source*
Reason for selection of (181902) 1999 RD_{215}: Early discovery; Brown (2020): "probably not" dwarf planet
Relationships between (181902) 1999 RD_{215} and other Exotica Catalog objects: Orbital primary: Sun [150]

Sednoid: 541132 Leleākūhonua [052]

Type also known as: Inner Oort Cloud object
Type description: Highly eccentric orbit with perihelion outside ~ 60 AU and aphelion at hundreds or thousands of AUs; not subject to exosolar influences nor gravity of giant planets
Type references: Sheppard et al. (2019)

541132 Leleākūhonua *is Solar System source*
541132 Leleākūhonua also known as: (541132) 2015 TG_{387}
Reason for selection of 541132 Leleākūhonua: Known example that is confidently not dwarf planet
Notes on 541132 Leleākūhonua: Radius: 110^{+14}_{-10} km (Buie et al. 2020)
Works relating 541132 Leleākūhonua to type: Sheppard et al. (2019)
General works about 541132 Leleākūhonua: Sheppard et al. (2019); Jet Propulsion Laboratory (2020a)
Relationships between 541132 Leleākūhonua and other Exotica Catalog objects: Orbital primary: Sun [150]

1.1.4 Minor satellites

1.1.4.1 Compositional classification

Rocky satellite: Phobos [053]

Type description: Composition dominated by non-volatile materials; moderate density

Phobos *is Solar System source*
Reason for selection of Phobos: One of two minor body examples around planets, and larger of two
Caveats about selection of Phobos: Phobos and Deimos have lower density ($\sim 2\ \mathrm{g\,cm^{-3}}$) than silicate rock, implying they are either porous or have icy interiors.
General works about Phobos: Jet Propulsion Laboratory (2020b); Rosenblatt (2011)
Relationships between Phobos and other Exotica Catalog objects: Orbital primary: Mars [082]

Icy satellite: Amalthea [054]

Type description: Volatile materials make up a large part of the satellite's mass; low density but $\sim 1\ \mathrm{g\,cm^{-3}}$

Amalthea *is Solar System source*
Reason for selection of Amalthea: Relatively nearby; largest of Jupiter's inner minor satellites; elsewhere in catalog
Notes on Amalthea: Density: $0.86\ \mathrm{g\,cm^{-3}}$
Works relating Amalthea to type: Anderson et al. (2005)
General works about Amalthea: Anderson et al. (2005); Thomas et al. (1998)
Relationships between Amalthea and other Exotica Catalog objects: Orbital primary: Jupiter [113]

Egg satellite: Methone [055]

Type description: Satellite is made of fine powder with very high porosity; in hydrodynamic equilibrium; very low density $\ll 1\ \mathrm{g\,cm^{-3}}$

Caveats about type: "Egg satellite" from a few brief mentions in Thomas et al. (2013); included because these objects are so extreme.
Type references: Thomas et al. (2013)

Methone *is Solar System source*
Reason for selection of Methone: Most striking example in images
Notes on Methone: Appears like a smooth ellipsoid in *Cassini* images; density: 0.31 $\mathrm{g\,cm^{-3}}$
General works about Methone: Thomas et al. (2013)
Relationships between Methone and other Exotica Catalog objects: Orbital primary: Saturn [064]

1.1.4.2 Orbital classification

The small classification system for satellites into regular, irregular, and "collisional shards" in Burns (1986) informs the orbital classification here.

Collisional shard: Amalthea [054]

Type description: Irregularly-shaped satellite in low eccentricity and low inclination orbit, generally interior to major satellites; possibly the result of collisional destruction of earlier inner satellites
Type references: Burns (1986)

Amalthea *is Solar System source*
Reason for selection of Amalthea: Explicitly listed example; relatively nearby and large
Caveats about selection of Amalthea: Low density and icy composition imply Amalthea may have actually formed in outer Jovian system, or was captured from Solar orbit
General works about Amalthea: Anderson et al. (2005); Thomas et al. (1998)
Relationships between Amalthea and other Exotica Catalog objects: Orbital primary: Jupiter [113]

Irregular (prograde) satellite: Himalia [056]

Type description: Small satellite in large but prograde inclination (< 90 deg); eccentricity can be large; captured from Solar orbit; may be collisionally evolved ruins of original captured satellites
Type references: Burns (1986); Jewitt & Haghighipour (2007); Bottke et al. (2010)

Himalia *is Solar System source*
Reason for selection of Himalia: Nearby example; largest around Jupiter
Notes on Himalia: Largest member of Himalia family of Jovian satellites
Relationships between Himalia and other Exotica Catalog objects: Orbital primary: Jupiter [113]

Irregular (retrograde) satellite: Phoebe [057]

Type description: Small satellite in large retrograde inclination (90–180 deg); eccentricity can be large; captured from Solar orbit; may be collisionally evolved ruins of original captured satellites
Type references: Burns (1986); Jewitt & Haghighipour (2007); Bottke et al. (2010)

Phoebe *is Solar System source*
Reason for selection of Phoebe: Explicitly listed in Burns (1986); well-studied during *Cassini* flyby
General works about Phoebe: Johnson & Lunine (2005); Porco et al. (2005)
Relationships between Phoebe and other Exotica Catalog objects: Orbital primary: Saturn [064]

Trojan satellite: Helene [058]

Type description: Satellite confined near stable Lagrange point (L_4 or L_5) of larger satellite and its host; known examples around Saturn

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Helene *is Solar System source*
Reason for selection of Helene: Largest of four known examples; located at Dione-Saturn L_4 point
General works about Helene: Thomas et al. (2013)
Relationships between Helene and other Exotica Catalog objects: Orbital primary: Saturn [064]

Co-orbital satellite: Epimetheus [059]

Type description: Satellite sharing orbital parameters with another; can have horseshoe or quasisatellite-like orbit in corotating frame; dynamics can be complicated

Epimetheus *is Solar System source*
Reason for selection of Epimetheus: One of two examples; orbit has more extreme horseshoe shape
Notes on Epimetheus: Partner is Janus
Works relating Epimetheus to type: Dermott & Murray (1981)
Relationships between Epimetheus and other Exotica Catalog objects: Orbital primary: Saturn [064]

Temporary Earth minimoon: 2006 RH_{120} [060]

Type also known as: Temporarily Captured Orbiter (TCO)
Type description: Very small (meter-scale) Arjuna object captured into orbit around Earth, far beyond Moon; completes one or more orbits around Earth with negative potential energy, but lifetime as satellite only months or years
Type references: Granvik et al. (2012)

2006 RH_{120} *is Solar System source*
Reason for selection of 2006 RH_{120}: First example
Caveats about selection of 2006 RH_{120}: Originally thought to be human space debris, possibly from Apollo mission, due to titanium paint-like spectrum – now thought to be natural
Notes on 2006 RH_{120}: Orbited Earth for 11 months; now is Earth co-orbital
Works relating 2006 RH_{120} to type: Kwiatkowski et al. (2009)
Relationships between 2006 RH_{120} and other Exotica Catalog objects: Orbital primary: Sun [150]

Alternative prototype(s): 2020 CD_3: more recent capture – will escape by May 2020 (de la Fuente Marcos & de la Fuente Marcos 2020b); 1991 VG: elsewhere in catalog – orbit not directly observed (de la Fuente Marcos & de la Fuente Marcos 2018)
Relationship to SETI: 2006 RH_{120} has size and possibly orbit of Earth-observing ETI probe (c.f., Benford 2019)?

Shepherd moon: Prometheus [061]

Type description: Satellite whose gravitational influence confines planetary ring to narrow orbit

Prometheus *is Solar System source*
Reason for selection of Prometheus: Well-known, large example
Notes on Prometheus: Shepherd of Saturn's F ring
Works relating Prometheus to type: Murray et al. (2005)
Relationships between Prometheus and other Exotica Catalog objects: Orbital primary: Saturn [064]

1.1.4.3 Rotational classification

Chaotic rotator: Hyperion [062]

Type description: Satellite with rotational axis that tumbles dramatically over short time scale

Hyperion *is Solar System source*
Reason for selection of Hyperion: Most famous example; well studied by *Cassini*
Notes on Hyperion: Has bizarre "sponge" appearance
Works relating Hyperion to type: Wisdom et al. (1984)
General works about Hyperion: Thomas et al. (2007a)
Relationships between Hyperion and other Exotica Catalog objects: Orbital primary: Saturn [064]

1.1.5 Planetesimals

White dwarf bodies: WD 1145+017 [063]

Type description: Debris orbiting white dwarf from larger disintegrating planetary bodies

WD 1145+017 *is sidereal source*

Reason for selection of WD 1145+017: First known example; well-studied
Notes on WD 1145+017: Discovered through frequent transits of debris
Works relating WD 1145+017 to type: Vanderburg et al. (2015); Xu et al. (2016); Gänsicke et al. (2016)

1.1.6 Circumplanetary bodies

Planetary ring: Saturn [064]

Type description: Largely symmetrical, very geometrically thin annulus of dust and small bodies (up to meter-scale) encircling planet (possibly including minor planets); can be optically thick; can have sharp edges; can have intricate radial structure
Type references: Ockert-Bell et al. (1999a); Verbiscer et al. (2009); Cuzzi et al. (2010); Renner et al. (2014); Braga-Ribas et al. (2014); Ockert-Bell et al. (1999b); Spahn et al. (2019)

Saturn *is Solar System source*
Reason for selection of Saturn: Most famous example; extremely well-studied
Notes on Saturn: Our focus will be on the prominent, discrete A, B, C, and F rings; not the outlying G, E or Phoebe rings
Works relating Saturn to type: Cuzzi et al. (2010); Tiscareno et al. (2019)
Relationships between Saturn and other Exotica Catalog objects: Hosts (is primary of): Methone [055], Phoebe [057], Helene [058], Epimetheus [059], Prometheus [061], Hyperion [062], Titan [102], Enceladus [107], Mimas [546], Iapetus [547], Tethys [548]; Orbital primary: Sun [150]

Ring arc: Neptune [065]

Type description: Radial asymmetry in planetary ring resulting in arc of enhanced density

Neptune *is Solar System source*
Reason for selection of Neptune: First discovered example; host elsewhere in catalog
Works relating Neptune to type: Hubbard et al. (1986); Dumas et al. (1999); Renner et al. (2014)
General works about Neptune: Helled et al. (2011)
Relationships between Neptune and other Exotica Catalog objects: Orbital primary: Sun [150]; Hosts (is primary of): Triton [103], Proteus [542], Neso [543]

Lagrange point dust cloud: L_5 Kordylewsky cloud [066]

Type description: Dust cloud located near planet-satellite stable Lagrange point
Caveats about type: Existence has been disputed due to difficulty of imaging and theoretical stability problems (e.g., Roosen & Wolff 1969)

L_5 Kordylewsky cloud *is Solar System source*
Reason for selection of L_5 Kordylewsky cloud: Known example
Notes on L_5 Kordylewsky cloud: Possibly transient
Works relating L_5 Kordylewsky cloud to type: Slíz-Balogh et al. (2019)

1.1.7 Interstellar minor bodies

Interstellar comet: 2I/Borisov [067]

Type description: Comet similar to those in Solar System in interstellar space; becomes active if it enters Solar System and approaches Sun
Type references: Moro-Martín et al. (2009); Jura (2011); Cook et al. (2016); Jewitt et al. (2020)

2I/Borisov *is Solar System source*
2I/Borisov also known as: C/2019 Q4 (Borisov)
Reason for selection of 2I/Borisov: Only known example; observed by Breakthrough Listen
Works relating 2I/Borisov to type: Guzik et al. (2020); Jewitt et al. (2020)

‘Oumuamua-type: 1I/‘Oumuamua [068]

Type description: Object with anomalous flat or needle-like shape in interstellar space; limited signs of cometary behavior, but experiences non-gravitational acceleration presumed to be result of comet-like activity; possibly fragment of comet surviving close passage with Sun

1I/'Oumuamua *is Solar System source*
1I/'Oumuamua also known as: 1I/2017 U1
Reason for selection of 1I/'Oumuamua: Only known example; observed by Breakthrough Listen
Notes on 1I/'Oumuamua: Limited understanding because only observed after perihelion
Works relating 1I/'Oumuamua to type: Meech et al. (2017); Micheli et al. (2018); 'Oumuamua ISSI Team et al. (2019)
General works about 1I/'Oumuamua: 'Oumuamua ISSI Team et al. (2019); Loeb (2018); Micheli et al. (2018); Meech et al. (2017)

Relationship to SETI: 1I/'Oumuamua properties claimed to be evidence of ETI light sail (Bialy & Loeb 2018; Loeb 2018)

1.1.8 Circumstellar disks

1.1.8.1 Young planetary system disks

Protoplanetary disk: TW Hya [069]

Type description: Optically thick disk of material surrounding young star, which can condense into future planetary system or accrete onto star; continuously extends from small inner radius to size of stellar system, with only thin gaps opened by planets
Type references: Williams & Cieza (2011); ALMA Partnership et al. (2015)

TW Hya *is sidereal source*
Reason for selection of TW Hya: Nearest example; well-studied
Caveats about selection of TW Hya: Frequently called transition disk because of inner gap – gap is only ~ 1 AU in radius, small compared to other transition disks; relatively old (3–10 Myr) – massive
Notes on TW Hya: Multiple gaps cleared by planets observed with ALMA
Works relating TW Hya to type: Andrews et al. (2012); Bergin et al. (2013); Andrews et al. (2016b)
General works about TW Hya: Sokal et al. (2018)

Alternative prototype(s): HL Tau: striking gap structure, young ($\lesssim 2$ Myr) – three times further away (ALMA Partnership et al. 2015)

Dipper: EPIC 203937317 [070]

Type description: Young star with frequent, deep and day-long dimming episodes; thought to be occultations by circumstellar disk structures
Notes on type: Dippers more specifically refers to late-type stars with moderate dimming events, with occulting bodies apparently all at magnetic corotation radius, but there are also the UX Ori variables: early-type stars with more extreme (~ 2 mag), longer occultations
Type references: Herbst et al. (1994); Herbst & Shevchenko (1999); Ansdell et al. (2016, 2020)

EPIC 203937317 *is sidereal source*
Reason for selection of EPIC 203937317: Most cited of Ansdell et al. (2016)
General works about EPIC 203937317: Bodman et al. (2017)

Alternative prototype(s): UX Ori: explicit prototype of UX Ori subclass, with larger host star mass (Herbst et al. 1994)

Transition disk: GM Aur [071]

Type description: Optically thick annulus of material surrounding young star; large (of order ~ 10 AU) cavity immediately surrounding star mostly cleared of dust
Type references: Andrews et al. (2011); Espaillat et al. (2014); van der Marel et al. (2016)

GM Aur *is sidereal source*
Reason for selection of GM Aur: Well-studied; strong evidence for wide gap; explicitly called transition disk in several references

Notes on GM Aur: Disk is 25 times less massive than TW Hya disk; inner gap is $\sim$ 20–35 AU in radius
Works relating GM Aur to type: Calvet et al. (2005); Hughes et al. (2009); Oh et al. (2016); Macías et al. (2018)

1.1.8.2 Debris disk

Hughes et al. (2018) informed our grouping of debris disks into cold, warm, and hot/exozodis.

Cold debris disk (Kuiper analog): τ Cet [072]

Type description: Optically thin dust disk sustained by collisional griding in star's Edgeworth-Kuiper belt; cold dust, visible in FIR; host star frequently Gyr old
Type references: Wyatt (2008); Hughes et al. (2018); Poppe et al. (2019)

τ **Cet** *is sidereal source*
Reason for selection of τ *Cet:* Very well-studied; relatively pure cold disk with little sign of warm dust; in I17
Caveats about selection of τ *Cet:* Indications of hot dust found
Notes on τ *Cet:* Inner edge of disk at 6 AU; star is 10 Gyr old, but disk is more massive than Kuiper Belt
Works relating τ *Cet to type:* Greaves et al. (2004); di Folco et al. (2007); MacGregor et al. (2016)
τ *Cet in I17*

Alternative prototype(s): Solar Kuiper Belt: nearest example, well studied – too big on sky to survey; Vega: early discovery – further away, also has warm debris disk

Warm debris disk (asteroidal): κ Psc [073]

Type description: Optically thin dust disk sustained by collisional griding in star's equivalent of main asteroid belt; warm dust, visible in MIR; host star frequently Gyr old
Type references: Wyatt (2008); Trilling et al. (2008); Hughes et al. (2018)

κ **Psc** *is sidereal source*
Reason for selection of κ *Psc:* Most cited of Morales et al. (2016) and Ballering et al. (2017) lacking cold dust; in I17
Works relating κ *Psc to type:* Morales et al. (2016); Ballering et al. (2017)
κ *Psc in I17*

Alternative prototype(s): Vega: early discovery, closer – also has cold debris disk

Hot debris disk: Altair [074]

Type also known as: Exozodi
Type description: Optically thin disk of small dust grains generated recently by minor bodies; includes Solar System zodiacal dust; hot dust, visible in NIR; host star frequently Gyr old
Type references: Nesvorný et al. (2010); Hughes et al. (2018)

Altair *is sidereal source*
Reason for selection of Altair: Star well-studied; most significant K-band excess in Absil et al. (2013), no sign of warm or cold dust
Notes on Altair: NIR excess is variable
Works relating Altair to type: Absil et al. (2013); Nuñez et al. (2017)
Altair in I17

Alternative prototype(s): Solar zodiacal light: nearest example, well studied – too big on sky to survey

Extreme debris disk: NGC 2547 ID8 [075]

Type description: Massive dust disk formed from the debris of protoplanet collisions during oligarchic growth phase of planet formation; infrared excess $\gtrsim 1\%$ of stellar luminosity; host star is tens of Myrs old
Type references: Meng et al. (2014, 2015)

NGC 2547 ID8 *is sidereal source*
Reason for selection of NGC 2547 ID8: Explicit prototype
Works where NGC 2547 ID8 referred to as prototype: Meng et al. (2015)
Works relating NGC 2547 ID8 to type: Meng et al. (2012, 2014)

Planetary collision disk: BD+20 307 [076]

Type description: Massive dust disk formed by collision of mature planetary bodies, Gyr after star formation
Type references: Theissen & West (2017)

BD+20 307 *is sidereal source*
Reason for selection of BD+20 307: First discovered
Notes on BD+20 307: Dustiest known star older than 1 Gyr as of Weinberger et al. (2011)
Works relating BD+20 307 to type: Song et al. (2005); Zuckerman et al. (2008); Weinberger et al. (2011)

Post-stellar (rejuvenated) debris disk: NGC 7293 central star [077]

Type description: Debris disk formed during post main-sequence evolution, when mass loss destabilizes Kuiper Belt analogs and leads to collisions; large and cold
Type references: Bilíková et al. (2012)

NGC 7293 central star *is sidereal source*
Reason for selection of NGC 7293 central star: First discovered; elsewhere in catalog
Works relating NGC 7293 central star to type: Su et al. (2007)
Relationships between NGC 7293 central star and other Exotica Catalog objects: Within the sky region occupied by: Helix Nebula [365]

Post-stellar (tidal disruption) debris disk: G29-38 [078]

Type description: Debris disk formed when minor body comes within tidal radius of collapsed star; compact and hot
Type references: Jura et al. (2007); Farihi et al. (2009); Barber et al. (2012)

G29-38 *is sidereal source*
G29-38 also known as: ZZ Psc
Reason for selection of G29-38: First recognized; most cited of Barber et al. (2012)
Works relating G29-38 to type: Jura (2003)

Post-stellar (evaporation) debris disk: WD J0914+1914 [079]

Type description: Debris disk formed from material evaporated off giant planet by collapsed star's ultraviolet radiation

WD J0914+1914 *is sidereal source*
Reason for selection of WD J0914+1914: Only known example
Caveats about selection of WD J0914+1914: Donor planet may actually be tidally disrupted
Works relating WD J0914+1914 to type: Gänsicke et al. (2019); Veras & Fuller (2020)
General works about WD J0914+1914: Gänsicke et al. (2019); Veras & Fuller (2020)

1.2 Solid planetoid

A phylum covering the major planets, dwarf planets, and major satellites.

Objects in this family range from a few hundred kilometers to a bit over ten thousands kilometers in radius, and they are round because they are in hydrostatic equilibrium. They are mostly "solid", although they can have substantial internal or external liquid oceans. Oceans that contribute a large fraction of the mass, if they exist, are underneath a solid crust. Essentially, these are the round planetoids that can be landed on. Solid planetoids can have rich geologies and interior evolution.

There is probably no strict delineation between these, with relatively thin atmospheres, and the giant planets, which have thick fluid envelopes.

1.2.1 Major planets

We use the terms "hot", "warm", "temperate", and "cold" to group by insolation. Cold planets are outside the conventional habitable zone (roughly taken to be $\lesssim 0.25$ Earth), temperate planets are within the conventional habitable zone (~ 0.25–2 Earth), warm planets are interior to the habitable zone but with insolations $\lesssim 100$ Earth, and hot planets have insolations $\gtrsim 100$ Earth. The distinction between "warm" and "hot" carries over from the giant planets, where warm planets around Sunlike stars are defined by period or semimajor axis (Dong et al. 2014; Huang et al. 2016; Petrovich & Tremaine 2016). The insolation range for "temperate" planets was chosen somewhat arbitrarily, partly to include Mars on the outside and leave no gaps with the "warm" planets as defined in the literature. Kopparapu et al. (2014) finds habitable zone boundaries that range from 0.8–1.4 Earth on the inside (generally near 1.0 AU) to 0.2–0.4 Earth on the outside. All the "temperate" Prototypes have insolations of 0.43–1.1 Earth, a more conservative range, with the exception of the temperate Jupiter HD 93083b with 1.8 Earth.

1.2.1.1 Compositional classification

Mercury (warm): Mercury [080]

Type description: Mass dominated by large iron core; thin mantle; mass smaller than Earth

Mercury *is Solar System source*

Reason for selection of Mercury: In Solar System; extremely well-studied; known example; elsewhere in catalog

Notes on Mercury: Radius: 0.38 $R_\oplus$; mass: 0.055 $M_\oplus$; insolation: 6.6 Earth (warm)

Works relating Mercury to type: Benz et al. (2007)

General works about Mercury: Benz et al. (2007); Margot et al. (2007)

Relationships between Mercury and other Exotica Catalog objects: Orbital primary: Sun [150]

Supermercury: K2-229 b [081]

Type description: Mass dominated by large iron core; thin mantle; mass larger than Earth

K2-229 b *is sidereal source*

Reason for selection of K2-229 b: Only known example

Notes on K2-229 b: Radius: 1.3 $R_\oplus$; mass: 2.6 $M_\oplus$; insolation: 2,500 Earth (hot);

Works relating K2-229 b to type: Santerne et al. (2018)

1.2.1.2 Size classification

The analyses by the *Kepler* team classify planets by radius. The categories are: < 1.25 $R_\oplus$ (Earths), 1.25–2 $R_\oplus$ (Super-Earth), 2–6 $R_\oplus$ (Neptune), 6–15 $R_\oplus$ (Jupiter), and > 15 $R_\oplus$ (non-planetary) (Borucki et al. 2011; Batalha et al. 2013).

This is a rough guide to our classifications, but some tweaks need to be made. First, there appears to be a transition from rocky to volatile compositions around 1.5 $R_\oplus$ (Rogers 2015; Fulton et al. 2017). Second, planets detected only through the radial velocity method have no radii. We use the Weiss & Marcy (2014) mass-radius relationship to guide mass ranges for the types. Third, we add a sub-Earth category, since it seems reasonable that a planet like Mars, or certainly the Moon, would have different prospects for habitability than one the size of Earth (Wordsworth 2016).

Planets detected by only radial velocity method have merely lower limits on their mass; the measured quantity is $M \sin i$, where $\sin i = 0$ for a face-on orbit and 1 for an edge-on orbit. As a guide, note that the mean value of $\sin i$ is $\pi/4$, when averaged over all orbital orientations.

1.2.1.2.1 Sub-Earths

In this work, a solid planetoid with radius smaller than 0.75 $R_\oplus$, so that the radius range for Earths is centered on 1 $R_\oplus$. This also is about halfway between the radii of Mars and Venus. For objects with unknown radius, a solid planetoid with mass smaller than 0.4 $M_\oplus$ from the Weiss & Marcy (2014) relation.

Sub-Earth (temperate): Mars [082]

Mars *is Solar System source*

Reason for selection of Mars: In Solar System; extremely well-studied.

Notes on Mars: Radius: 0.53 $R_\oplus$; mass: 0.11 $M_\oplus$; insolation: 0.43 Earth

General works about Mars: Bibring et al. (2006); Carr & Head (2010); Wordsworth (2016); Kieffer (2007); Kieffer et al. (2006); Portyankina et al. (2010)

Relationships between Mars and other Exotica Catalog objects: Hosts (is primary of): Phobos [053]; Orbital primary: Sun [150]

Sub-Earth (warm): Mercury [080]

Mercury *is Solar System source*
Reason for selection of Mercury: In Solar System; extremely well-studied; elsewhere in catalog.
Caveats about selection of Mercury: Abnormal core-dominated composition.
Notes on Mercury: Radius: 0.38 $R_\oplus$; mass: 0.055 $M_\oplus$; insolation: 6.6 Earth
General works about Mercury: Benz et al. (2007); Margot et al. (2007)
Relationships between Mercury and other Exotica Catalog objects: Orbital primary: Sun [150]

Sub-Earth (hot): Kepler 444 d [083]

Kepler 444 d *is sidereal source*
Reason for selection of Kepler 444 d: Elsewhere in catalog
Caveats about selection of Kepler 444 d: Density is much lower than expected for rocky planets.
Notes on Kepler 444 d: Radius: 0.54 ± 0.02 $R_\oplus$; mass: 0.04 $M_\oplus$; insolation: ~ 110 Earth
Works relating Kepler 444 d to type: Mills & Fabrycky (2017)
General works about Kepler 444 d: Buldgen et al. (2019); Campante et al. (2015)
Works about host of Kepler 444 d: Buldgen et al. (2019)

1.2.1.2.2 Earths

In this work, a solid planetoid with radius in range 0.75–1.25 $R_\oplus$. For objects with unknown radius, a solid planetoid with mass in the range $0.4 - -2$ $M_\oplus$, rounding the results from the Weiss & Marcy (2014) relation.

Notes on general class: "Earth" not an endorsement of habitability or the presence of life or technosignatures.

Earth (temperate): Proxima b [084]

Type references: Kasting & Catling (2003); Petigura et al. (2013)

Proxima b *is sidereal source*
Reason for selection of Proxima b: Famous example; nearest non-Solar example; star in I17
Caveats about selection of Proxima b: Radial velocity detection only
Notes on Proxima b: $M \sin i$: 1.3 $M_\oplus$; insolation: 0.66 Earth; planned target of Breakthrough Starshot
Works relating Proxima b to type: Anglada-Escudé et al. (2016); Turbet et al. (2016)
Proxima b in I17
Relationships between Proxima b and other Exotica Catalog objects: Gravitationally bound to: α Cen AB [321]

Alternative prototype(s): Earth: best studied, closest – technosignatures already detected (e.g., RFI; see also Sagan et al. 1993), difficult to study as a whole from the ground except through reflections off Moon (McKinley et al. 2013; DeMarines et al. 2019)

Earth (warm): Venus [085]

Type references: Kasting (1988); Leconte et al. (2013)

Venus *is Solar System source*
Reason for selection of Venus: In Solar System; best studied; surface conditions definitely not habitable
Caveats about selection of Venus: May have been temperate and habitable in early Solar System (Way et al. 2016). The current insolation is technically outside of the notional 2.0 Earth boundary, although Venus is certainly not temperate.
Notes on Venus: Radius: 0.95 $R_\oplus$; mass: 0.81 $M_\oplus$; insolation: 1.9 Earth
Works relating Venus to type: Kasting (1988)
General works about Venus: Solomatov & Moresi (1996); Way et al. (2016); Kasting (1988); Jet Propulsion Laboratory (2020c); Nimmo & McKenzie (1998)
Relationships between Venus and other Exotica Catalog objects: Orbital primary: Sun [150]

Earth (hot): Kepler 78 b [086]

Type also known as: Ultra-Short Period (USP) planet
Type references: Dai et al. (2019)

Kepler 78 b *is sidereal source*
Reason for selection of Kepler 78 b: Well-studied, according to Dai et al. (2017)
Notes on Kepler 78 b: Radius: 1.23 ± 0.02 $R_\oplus$; mass: 1.8 ± 0.2 $M_\oplus$; insolation: 4,000 Earth
Works relating Kepler 78 b to type: Sanchis-Ojeda et al. (2013); Dai et al. (2019)

1.2.1.2.3 Super-Earths

In this work, a solid planetoid with radius larger than 1.25 $R_\oplus$ (less than 1.5 $R_\oplus$ if mass is unknown, although larger examples are known). For objects with unknown radius, rounding the results from the Weiss & Marcy (2014) relation implies a solid planetoid with mass in the range $2 - -4.5$ $M_\oplus$. More massive examples (up to ~ 10 $M_\oplus$) are known, however, whose rocky natures have been confirmed with transits (e.g., Winn et al. 2011; Gandolfi et al. 2017; Dittmann et al. 2017).

Super-Earth (cold): Barnard's star b [087]

Barnard's star b *is sidereal source*
Reason for selection of Barnard's star b: Nearest likely example; star well-studied; star in I17
Caveats about selection of Barnard's star b: Radial velocity detection only, mass close to typical threshold for giant planets if $\sin i = \pi/4$ (4.1 $M_\oplus$)
Notes on Barnard's star b: $M \sin i$: 3.2 $M_\oplus$; insolation: 0.02 Earth
Works relating Barnard's star b to type: Ribas et al. (2018)
Barnard's star b in I17

Super-Earth (temperate): LHS 1140 b [088]

LHS 1140 b *is sidereal source*
Reason for selection of LHS 1140 b: Relatively nearby example; detected in both transits and radial velocity; density confirms solid planetoid status
Caveats about selection of LHS 1140 b: Radius and mass large compared to 1.5 $R_\oplus$ transition – density implies rocky composition
Notes on LHS 1140 b: Radius: 1.72 ± 0.03 $R_\oplus$; mass: 7.0 $M_\oplus$; density: 7.5 $\mathrm{g\,cm^{-3}}$; insolation: 0.39 Earth, slightly lower than Mars
Works relating LHS 1140 b to type: Dittmann et al. (2017)
General works about LHS 1140 b: Pinchuk et al. (2019); Ment et al. (2019)

Super-Earth (warm): HD 40307 f [089]

HD 40307 f *is sidereal source*
Reason for selection of HD 40307 f: Relatively nearby example; mass plausibly in super-Earth range; existence quite certain; in I17
Caveats about selection of HD 40307 f: Radial velocity detection only, mass slightly above typical threshold for giant planets if $\sin i = \pi/4$ (4.6 $M_\oplus$)
Notes on HD 40307 f: $M \sin i$: 3.63 ± 0.60 $M_\oplus$; insolation: 3.7 Earth
Works relating HD 40307 f to type: Díaz et al. (2016)
General works about HD 40307 f: Tuomi et al. (2013); Díaz et al. (2016)
HD 40307 f in I17

Super-Earth (hot): 55 Cnc e [090]

55 Cnc e *is sidereal source*
55 Cnc e also known as: ρ_1 Cnc e
Reason for selection of 55 Cnc e: Well-studied system; detected in both transits and radial velocity; star in I17
Caveats about selection of 55 Cnc e: Likely to have relatively thick atmosphere envelope of $3 - -8\%$ of radius; radius and mass

large compared to 1.5 $R_\oplus$ – mean density implies mostly rocky composition
Notes on 55 Cnc e: Mass: 8.0–8.6 $M_\oplus$; radius: 1.9–2.0 $R_\oplus$; density: 5.8–6.7$\,\mathrm{g\,cm^{-3}}$; insolation: 2,500 Earth
Works relating 55 Cnc e to type: Winn et al. (2011)
General works about 55 Cnc e: Bourrier et al. (2018); Crida et al. (2018)
55 Cnc e in I17

1.2.1.3 Orbital dynamics classification

Resonant chain (solid) planets: TRAPPIST-1 bcdefg [091]

Type description: Multiple (solid) planet system in resonance with each other; orbital periods have simple integer ratios
Notes on type: May be a sign of coordinated migration of planets (e.g., Terquem & Papaloizou 2007; Mills et al. 2016)
Type references: Christiansen et al. (2018); MacDonald & Dawson (2018)

TRAPPIST-1 bcdefg *is sidereal source*
Reason for selection of TRAPPIST-1 bcdefg: Spectacular example with six to seven planets in resonance (none giant planets); elsewhere in catalog; nearby and well-studied
Notes on TRAPPIST-1 bcdefg: Ratios of succeeding periods are 8:5 (cb), 5:3 (dc), 3:2 (ed), 3:2 (fe), 4:3 (gf) (Gillon et al. 2017); TRAPPIST-1h is in a three-body resonance with f and g, along with several other trios, according to Luger et al. (2017)
Works relating TRAPPIST-1 bcdefg to type: Gillon et al. (2017); Luger et al. (2017)
General works about TRAPPIST-1 bcdefg: Gillon et al. (2017); Gonzales et al. (2019); Pinchuk et al. (2019)

Alternative prototype(s): K2-138 bcdef: five planets in resonant chain, each succeeding pair with 3:2 period ratios – planets are larger (1.6–3.6 $R_\oplus$) (Christiansen et al. 2018), possibly indicating they are giants (c.f., Lopez et al. 2019)

1.2.1.4 Giant planet core

Giant planet core: TOI 849 b [092]

Type description: Former solid core of gas/ice giant; envelope has been ablated away leaving it exposed; very massive relative to other solid planetoids

TOI 849 b *is sidereal source*
Reason for selection of TOI 849 b: Known example
Notes on TOI 849 b: Mass: 39.1 $M_\oplus$; $\rho = 5.2\ \mathrm{g\,cm^{-3}}$
Works relating TOI 849 b to type: Armstrong et al. (2020)

1.2.1.5 Disintegrating planets

Disintegrating planet: KIC 12557548 b [093]

Type description: Hot solid planet being evaporated by heat of star; has comet-like dust trail seen in planetary transits
Type references: Rappaport et al. (2012); Sanchis-Ojeda et al. (2015)

KIC 12557548 b *is sidereal source*
KIC 12557548 b also known as: Kepler 1520 b
Reason for selection of KIC 12557548 b: Explicit prototype; first discovered example
Notes on KIC 12557548 b: Planetoid may be smaller than Mercury
Works where KIC 12557548 b referred to as prototype: Ridden-Harper et al. (2018)
Works relating KIC 12557548 b to type: Rappaport et al. (2012); Brogi et al. (2012); Budaj (2013); Croll et al. (2014)

1.2.1.6 Post-stellar planets

Pulsar planet: PSR B1257+12 ABC [094]

Type description: Terrestial-mass planets orbiting pulsar; origin very unclear
Type references: Podsiadlowski (1993); Phinney & Hansen (1993); Kerr et al. (2015); Martin et al. (2016)

PSR B1257+12 ABC *is sidereal source*
Reason for selection of PSR B1257+12 ABC: Known examples
Notes on PSR B1257+12 ABC: Masses: 0.02 $M_\oplus$ (A), 4.3 ± 0.2 $M_\oplus$ (B), 3.9 ± 0.2 $M_\oplus$ (C)

Works relating PSR B1257+12 ABC to type: Wolszczan & Frail (1992); Konacki & Wolszczan (2003)
General works about PSR B1257+12 ABC: Konacki & Wolszczan (2003); Wolszczan & Frail (1992); Schneider et al. (2011)

1.2.2 Dwarf planets

See Tancredi & Favre (2008) for suggested dwarf planet criteria. Dwarf planets in the Solar System are classed according to the spectral type and orbit, similarly to minor bodies (Section 1.1). With the exception of Sedna, only the IAU-recognized dwarf planets (Ceres, Pluto, Eris, Makemake, Haumea) are listed as dwarf planets.

1.2.2.1 Spectral classification

C-complex: 1 Ceres [095]

Type description: Carbonaceous; spectral class group in B02; includes G class of T84

1 Ceres *is Solar System source*
Reason for selection of 1 Ceres: Known example
Notes on 1 Ceres: Spectral classification: G (T84), G (T89), C (B02); well-studied by *Dawn*
General works about 1 Ceres: Ruesch et al. (2016); Jet Propulsion Laboratory (2020a); Russell et al. (2016); Park et al. (2016)
Relationships between 1 Ceres and other Exotica Catalog objects: Orbital primary: Sun [150]

BB-type: 136199 Eris [096]

Type description: Icy dwarf planet with neutral colors
Type references: Fulchignoni et al. (2008)

136199 Eris *is Solar System source*
Reason for selection of 136199 Eris: Known example; listed as BB in Fulchignoni et al. (2008) and Barucci et al. (2008); elsewhere in catalog
General works about 136199 Eris: Brown & Schaller (2007); Brown et al. (2005a); Sicardy et al. (2011); Jet Propulsion Laboratory (2020a)
Relationships between 136199 Eris and other Exotica Catalog objects: Orbital primary: Sun [150]

BR-type: 134340 Pluto [097]

Type description: Icy dwarf planet with intermediate (somewhat red) color
Type references: Fulchignoni et al. (2008)

134340 Pluto *is Solar System source*
Reason for selection of 134340 Pluto: Known example; listed as BR in Fulchignoni et al. (2008) and Barucci et al. (2008); elsewhere in catalog
Notes on 134340 Pluto: Studied by *New Horizons* during flyby
General works about 134340 Pluto: Stern et al. (2018); Nimmo et al. (2016); McKinnon et al. (2016)
Relationships between 134340 Pluto and other Exotica Catalog objects: Orbital primary: Sun [150]; Hosts (is primary of): Charon [549]

RR-type: 90377 Sedna [098]

Type description: Icy dwarf planet with ultrared color
Type references: Barucci et al. (2005); Fulchignoni et al. (2008)

90377 Sedna *is Solar System source*
Reason for selection of 90377 Sedna: Likeliest candidate; listed as RR in Fulchignoni et al. (2008) and Barucci et al. (2008); elsewhere in catalog
Caveats about selection of 90377 Sedna: Not officially classified by IAU as dwarf planet – Brown (2020): "near certainty" of dwarf planet status
General works about 90377 Sedna: Jet Propulsion Laboratory (2020a); Morbidelli & Levison (2004); Brown et al. (2004); Pál et al. (2012)
Relationships between 90377 Sedna and other Exotica Catalog objects: Orbital primary: Sun [150]

1.2.2.2 Orbital classification

Because the current IAU definition of "dwarf planet" and major "planet" depend on whether a body's orbit is in the vicinity of other similarly sized bodies, arguably major planet and dwarf planet are orbital classifications as well. In practice, they are considered larger categories, hence the organization.

Main asteroid belt dwarf planet: 1 Ceres [095]

Type references: Vernazza et al. (2020)

1 Ceres *is Solar System source*
Reason for selection of 1 Ceres: Known example
Notes on 1 Ceres: Well-studied by *Dawn*
General works about 1 Ceres: Ruesch et al. (2016); Jet Propulsion Laboratory (2020a); Russell et al. (2016); Park et al. (2016)
Relationships between 1 Ceres and other Exotica Catalog objects: Orbital primary: Sun [150]

Plutino dwarf planet: 134340 Pluto [097]

Type description: Resonant Kuiper Belt dwarf planet in 3:2 resonance with Neptune; semimajor axis interior to bulk of Kuiper Belt

134340 Pluto *is Solar System source*
Reason for selection of 134340 Pluto: Only example
Notes on 134340 Pluto: Studied by *New Horizons* during flyby
General works about 134340 Pluto: Stern et al. (2018); Nimmo et al. (2016); McKinnon et al. (2016)
Relationships between 134340 Pluto and other Exotica Catalog objects: Orbital primary: Sun [150]; Hosts (is primary of): Charon [549]

Hot classical Kuiper Belt dwarf planet: 136472 Makemake [099]

Type description: Low to moderate eccentricity, moderate inclination Kuiper Belt dwarf planet not in resonace with Neptune; 39.4 AU $< a <$ 48.2 AU; "hot" refers to orbital dynamics, not physical temperature

136472 Makemake *is Solar System source*
Reason for selection of 136472 Makemake: Only officially classified example
Notes on 136472 Makemake: Semimajor axis: 45.4 AU; inclination: 29.0 deg
General works about 136472 Makemake: Parker et al. (2016); Ortiz et al. (2012)
Relationships between 136472 Makemake and other Exotica Catalog objects: Orbital primary: Sun [150]

Haumea family dwarf planet: 136108 Haumea [100]

Type description: Kuiper Belt dwarf planet sharing orbit with members of Haumea family; origin of family unclear
Type references: Brown et al. (2007); Pike et al. (2020)

136108 Haumea *is Solar System source*
Reason for selection of 136108 Haumea: Only example
General works about 136108 Haumea: Rabinowitz et al. (2006); Ragozzine & Brown (2009)
Relationships between 136108 Haumea and other Exotica Catalog objects: Orbital primary: Sun [150]

Detached dwarf planet: 136199 Eris [096]

Type also known as: Extended Scattered Disk Object (ESDO); Extended Disk Object (EDO)
Type description: Dwarf planet with orbit entirely exterior to Neptune; large semimajor axis (outside 2:1 resonance with Neptune) and generally large eccentricity (Gladman et al. 2008: $e > 0.24$)
Type references: Gladman et al. (2008)

136199 Eris *is Solar System source*
Reason for selection of 136199 Eris: Elsewhere in catalog; officially classified by IAU as dwarf planet
Works relating 136199 Eris to type: Brown et al. (2005a)
General works about 136199 Eris: Brown & Schaller (2007); Sicardy et al. (2011); Jet Propulsion Laboratory (2020a)
Relationships between 136199 Eris and other Exotica Catalog objects: Orbital primary: Sun [150]

Sednoid dwarf planet: 90377 Sedna [098]

Type also known as: Inner Oort Cloud object
Type description: Dwarf planet with highly eccentric orbit; perihelion outside ~ 60 AU and aphelion at hundreds or thousands of AUs; not subject to exosolar influences nor gravity of giant planets
Type references: Trujillo & Sheppard (2014)

90377 Sedna *is Solar System source*
Reason for selection of 90377 Sedna: Elsewhere in catalog; most extreme properties of near-certain dwarf planets; first example of Sednoid discovered
Caveats about selection of 90377 Sedna: Not officially classified by IAU as dwarf planet – Brown (2020): "near certainty" of dwarf planet status
Works relating 90377 Sedna to type: Brown et al. (2004); Morbidelli & Levison (2004)
General works about 90377 Sedna: Jet Propulsion Laboratory (2020a); Morbidelli & Levison (2004); Pál et al. (2012)
Relationships between 90377 Sedna and other Exotica Catalog objects: Orbital primary: Sun [150]

1.2.3 Major satellites

1.2.3.1 Compositional classification

Rocky major satellite: Moon [101]

Type description: Silicate dominated composition

Moon *is Solar System source*
Reason for selection of Moon: Extremely well-studied; visited by humans; one of two known examples
Notes on Moon: Basaltic volcanism prevalent $\gtrsim 3$ Gyr ago with some persisting to ~ 1 Gyr ago; possible evidence for minor volcanism in past 100 Myr (Braden et al. 2014)
General works about Moon: Hiesinger et al. (2003); Stevenson (1987); Jet Propulsion Laboratory (2020d); Asphaug (2014); Haruyama et al. (2009)

Alternative prototype(s): Io: also silicate dominated composition – much further away, environment more like that of icy satellite aside from tidal heating
Relationship to SETI: The Moon is suggested to hold meteorites from Earth recording ancient "alternate" life (Davies & Lineweaver 2005); could be location of probes or artifacts (Arkhipov & Graham 1996; Davies & Wagner 2013); reflects Earth's radio emission (Moonbounce), allowing study of its radio technosignatures (McKinley et al. 2013; DeMarines et al. 2019)

Icy major satellite: Titan [102]

Type description: Mixture of frozen volatiles and rocky material

Titan *is Solar System source*
Reason for selection of Titan: Astrobiological interest; well-studied (including by lander)
Notes on Titan: Target of *Huygens* and planned target of *Dragonfly*; probable internal water-ammonia ocean; surface fluids are hydrocarbons, not water
Works relating Titan to type: Lorenz et al. (2008)
General works about Titan: Lorenz et al. (2008); Hayes (2016); Roe (2012)
Relationships between Titan and other Exotica Catalog objects: Orbital primary: Saturn [064]

1.2.3.2 Orbital classification

Retrograde moon: Triton [103]

Type description: Large satellite in irregular orbit; presumably captured from Solar orbit

Triton *is Solar System source*
Reason for selection of Triton: Known example
Notes on Triton: Has surface geysers and thin nitrogen atmosphere; water/ammonia ocean in geological past
Works relating Triton to type: Agnor & Hamilton (2006)

General works about Triton: Agnor & Hamilton (2006); Gaeman et al. (2012); Soderblom et al. (1990)
Relationships between Triton and other Exotica Catalog objects: Orbital primary: Neptune [065]

Resonant chain moon: Europa [104]

Type description: Large satellite in resonance with other large satellite(s), with simple integer ratios between periods
Type references: Yoder (1979)

Europa *is Solar System source*
Reason for selection of Europa: Nearby example; in resonance with both inner (Io) and outer (Ganymede) moons
General works about Europa: Schmidt et al. (2011); Roth et al. (2014); Kattenhorn & Hurford (2009)
Relationships between Europa and other Exotica Catalog objects: Orbital primary: Jupiter [113]

1.2.4 Geological classification

This "geological" classification is intended to very roughly sample the diversity of surface environments and histories in the Solar System, excluding the Earth itself.

Primordial world: Callisto [105]

Type description: Little to no ongoing endogenic surface modification or geological activity; exogenic modification by cratering

Callisto *is Solar System source*
Reason for selection of Callisto: Close, large example; little activity since formation
Notes on Callisto: Partial to no differentiation; target of planned JUICE mission
Works relating Callisto to type: Barr & Canup (2010)
Relationships between Callisto and other Exotica Catalog objects: Orbital primary: Jupiter [113]

Inactive world: Ganymede [106]

Type description: Little to no ongoing endogenic surface modification or geological activity, but endogenic activity in distant past; exogenic modification by cratering

Ganymede *is Solar System source*
Reason for selection of Ganymede: Close, large example
Notes on Ganymede: Differentiated, possibly with internal water oceans; target of planned JUICE mission
Works relating Ganymede to type: Barr & Canup (2010)
General works about Ganymede: Jet Propulsion Laboratory (2020d)
Relationships between Ganymede and other Exotica Catalog objects: Orbital primary: Jupiter [113]

Insolation-driven geology: Mars [082]

Type description: Geological activity driven by (sub)surface heating by Sun
Type references: Brown et al. (1990); Kirk et al. (1990); Kieffer et al. (2006); Kieffer (2007)

Mars *is Solar System source*
Reason for selection of Mars: Known likely example
Notes on Mars: Carbon dioxide geyser eruptions on Martian south polar ice cap, though to be sublimating gas from solar heating of translucent ices; results in "spiders" and variable dark fans (Kieffer et al. 2006; Kieffer 2007; Portyankina et al. 2010); Mars also has conventional volcanoes, most famously Olympus Mons
Works relating Mars to type: Kieffer et al. (2006); Kieffer (2007); Portyankina et al. (2010)
General works about Mars: Carr & Head (2010); Bibring et al. (2006); Wordsworth (2016)
Relationships between Mars and other Exotica Catalog objects: Hosts (is primary of): Phobos [053]; Orbital primary: Sun [150]

Alternative prototype(s): Triton: nitrogen geysers most often explained as driven by solar heating (Soderblom et al. 1990; Brown et al. 1990; Kirk et al. 1990) – may be driven by convection instead (Duxbury & Brown 1997)

Convective geology: 134340 Pluto [097]

Type description: Surface features resulting from solid-state convection

134340 Pluto *is Solar System source*
Reason for selection of 134340 Pluto: Known, spectacular example
Notes on 134340 Pluto: Convective cells prominent in Sputnik Planitia
Works relating 134340 Pluto to type: McKinnon et al. (2016)
General works about 134340 Pluto: Stern et al. (2018); Nimmo et al. (2016)
Relationships between 134340 Pluto and other Exotica Catalog objects: Orbital primary: Sun [150]; Hosts (is primary of): Charon [549]

Hydrological world: Titan [102]

Type description: Surface modification by atmosphere and surface fluids

Titan *is Solar System source*
Reason for selection of Titan: Most extreme atmosphere of satellites; only known besides Earth with standing liquid lakes and seas; astrobiological interest
Notes on Titan: Target of *Huygens* and planned target of *Dragonfly*; probable internal water-ammonia ocean; surface fluids are hydrocarbons, not water
Works relating Titan to type: Roe (2012); Hayes (2016)
General works about Titan: Lorenz et al. (2008); Hayes (2016); Roe (2012)
Relationships between Titan and other Exotica Catalog objects: Orbital primary: Saturn [064]

Alternative prototype(s): Earth

Stagnant lid world: Venus [085]

Type description: Geologically active world where crust has congealed into thick single layer/plate; no plate tectonics; activity may result in global resurfacing
Type references: Solomatov & Moresi (1996); Sleep (2000)

Venus *is Solar System source*
Reason for selection of Venus: Known, spectacular example
Notes on Venus: Possibly was Earth-like until past billion years (Way et al. 2016)
Works relating Venus to type: Solomatov & Moresi (1996); Nimmo & McKenzie (1998)
General works about Venus: Jet Propulsion Laboratory (2020c); Nimmo & McKenzie (1998); Way et al. (2016); Kasting (1988)
Relationships between Venus and other Exotica Catalog objects: Orbital primary: Sun [150]

Alternative prototype(s): Mars: better studied – probably less active

Tectonic world: Europa [104]

Type description: Surface modification by crustal motions and fracturing

Europa *is Solar System source*
Reason for selection of Europa: Close; striking example; astrobiological interest; studied by past and future probes
Notes on Europa: Famously has water ocean $\sim$ 10km below surface, with possible liquid habitats close to surface in chaos terrain; also likely has plumes; target of planned *Europa Clipper* mission; few craters
Works relating Europa to type: Kattenhorn & Hurford (2009)
General works about Europa: Schmidt et al. (2011); Roth et al. (2014); Kattenhorn & Hurford (2009)
Relationships between Europa and other Exotica Catalog objects: Orbital primary: Jupiter [113]

Alternative prototype(s): Earth

Cryovolcanic world: Enceladus [107]

Type description: Surface modification by eruptions of volatiles

Enceladus *is Solar System source*
Reason for selection of Enceladus: Striking example of ongoing eruptions; astrobiological interest; studied by past probes

Notes on Enceladus: Also has tectonic features and subsurface water sea/ocean; plumes in southern hemisphere, which has youngest surface; northern hemisphere is cratered and old

Works relating Enceladus to type: Porco et al. (2006)

General works about Enceladus: Spencer & Nimmo (2013); Jet Propulsion Laboratory (2020d)

Relationships between Enceladus and other Exotica Catalog objects: Orbital primary: Saturn [064]

Alternative prototype(s): Europa; 1 Ceres

Volcanic world: Io [108]

Type description: Silicate dominated composition; surface heavily modified by ongoing volcanism; few craters

Io *is Solar System source*

Reason for selection of Io: Known example; most spectacular example

Notes on Io: High internal heat flux from tidal heating; most volcanically active Solar System body

Works relating Io to type: McEwen et al. (2000); Veeder et al. (2012)

General works about Io: Khurana et al. (2011); McEwen et al. (2000); Jet Propulsion Laboratory (2020d)

Relationships between Io and other Exotica Catalog objects: Orbital primary: Jupiter [113]

Alternative prototype(s): Earth, Venus

1.3 Giant planets

A phylum covering the gas giants and ice giants. They are larger than the Earth, in hydrostatic equilibrium, and characterized by thick fluid envelopes that dominate their mass. Frequently they have relatively high internal heat luminosity, which dominates the heat flux if they are in the outer parts of their solar systems. Unlike members of the "star" phylum, these are thought to be formed by core accretion (gas accretion onto a solid core).

The two commonly recognized classes of giant planets are ice giants (Neptunes) and gas giants (Jupiters). To these, we add a "super-Jovian" class for planets that approach but do not exceed the threshold for deuterium burning, mainly to ensure good coverage over the possible ranges and densities of giant planets. As cool, old giant planets more massive than Jupiter are expected to have similar radii to Jupiter, the division in between gas giants and superjovians is defined by mass.

Giant exoplanets, and solid exoplanets to some extent, also are classified using temperature terms. Sometimes these are defined in terms of orbital periods or semimajor axis. We use the terms "hot", "warm", "temperate", and "cold". Cold planets receive too little insolation to be in the habitable zone, temperate planets receive the right amount of insolation to be in the habitable zone, and warm planets receive too much insolation to be in the habitable zone. These definitions depend on which prescription is used for the habitable zone; we usually leave this up to authors for temperate planets and select obvious examples for cold and warm planets. Very roughly, the insolation in the habitable zone is of order 0.25–2 Earth. Many cold planets are outside of the snow line, which may serve as another definition. Warm Jupiters have been defined as those with orbital periods between 10–100 days (Dong et al. 2014) or 10–200 days (Huang et al. 2016), or semi-major axes between 0.1–1 AU (Petrovich & Tremaine 2016). Either way, the maximum insolation for warm planets is 100 Earth, which we take as the boundary between warm and hot planets.

An additional subcategory classifies giant planets according to (non-main sequence) stellar host, with a final entry for a resonant chain system.

1.3.1 Ice giants

A giant planet whose composition is dominated by fluids of "ices" − volatiles of simple molecules (aside from hydrogen) like water and ammonia. "Ice" refers to a chemical composition; in the case of Uranus and Neptune, they are in a hot supercritical fluid phase. These planets also have thick hydrogen-helium envelopes and rocky cores.

While ice giants are generally thought to be less massive than gas giants, the existence of low-density, low-mass giant planets suggests that gas giants can be low mass as well. As a rough guide, $\sim 1.5\ R_\oplus$ seems to mark a transition from rocky super-Earths to ice giants, with giants dominant above $2\ R_\oplus$.

General references: Fortney & Nettelmann (2010); Dong & Zhu (2013)

Cold Neptune: Neptune [065]

Type references: Gould et al. (2006)

Neptune *is Solar System source*
Reason for selection of Neptune: In Solar System; well-studied; eponym
Notes on Neptune: Radius: 3.9 $R_\oplus$; mass: 17 $M_\oplus$; insolation: 0.0011 Earth
Works relating Neptune to type: Helled et al. (2011)
General works about Neptune: Hubbard et al. (1986); Renner et al. (2014); Helled et al. (2011); Dumas et al. (1999)
Relationships between Neptune and other Exotica Catalog objects: Orbital primary: Sun [150]; Hosts (is primary of): Triton [103], Proteus [542], Neso [543]

Alternative prototype(s): Uranus: in Solar System – anomalous properties

Temperate Neptune: Kepler 22 b [109]

Type references: Heller & Barnes (2013)

Kepler 22 b *is sidereal source*
Reason for selection of Kepler 22 b: Likelihood of being in habitable zone; early discovery
Caveats about selection of Kepler 22 b: Mass unknown – Rogers (2015): $< 2\%$ probability of being rocky
Notes on Kepler 22 b: Radius: 2.4 $R_\oplus$; insolation: 1.1 Earth
Works relating Kepler 22 b to type: Borucki et al. (2012); Kipping et al. (2013)

Warm Neptune: GJ 436 b [110]

GJ 436 b *is sidereal source*
Reason for selection of GJ 436 b: First discovered; nearby; detected in both transits and RV
Notes on GJ 436 b: Radius: 4.0 $R_\oplus$; mass: 25 $M_\oplus$; insolation: 28 Earth
Works relating GJ 436 b to type: Gillon et al. (2007); Lothringer et al. (2018)
General works about GJ 436 b: von Braun et al. (2012)
Works about host of GJ 436 b: von Braun et al. (2012)

Hot Neptune: HATS-P-26 b [111]

Type description: Around Sunlike stars, periods of only a few days, with temperatures $\gtrsim$ 1,000 K; very rare (the "short-period Neptune desert")
Type references: Mazeh et al. (2016)

HATS-P-26 b *is sidereal source*
Reason for selection of HATS-P-26 b: Neptune-sized; one of few found in literature; dedicated spectroscopic study exists
Caveats about selection of HATS-P-26 b: Density low compared to Neptune
Notes on HATS-P-26 b: Radius: 6.2 $R_\oplus$; mass: 19 $M_\oplus$; insolation: 170 Earth
General works about HATS-P-26 b: Hartman et al. (2011); Wakeford et al. (2017)

Mini-Neptune: GJ 1214 b [112]

Type also known as: Sub-Neptune
Type description: World with ice-dominated composition, but significantly smaller than Neptune, with radii $\sim$ 1.75–3.5 $R_\oplus$ (typically around 2.4 $R_\oplus$) and masses of order ~ 10 $M_\oplus$
Type references: Barnes et al. (2009); Fulton et al. (2017); Gandolfi et al. (2017); Venturini & Helled (2017)

GJ 1214 b *is sidereal source*
Reason for selection of GJ 1214 b: Well-studied, first discovered
Notes on GJ 1214 b: Radius: 2.65 $R_\oplus$; mass: 6.45 $M_\oplus$; insolation: 17 Earth
Works relating GJ 1214 b to type: Lopez et al. (2012); Weiss & Marcy (2014); Lavvas et al. (2019)
General works about GJ 1214 b: Charbonneau et al. (2009); Lavvas et al. (2019)

1.3.2 Gas giant

A giant planet whose composition is dominated by fluids of the “gases” molecular hydrogen and helium. The hydrogen and helium need not strictly be in gaseous phase. These planets are generally believed to have rocky cores, although their sizes and even existence is under debate.

General references: Fortney & Nettelmann (2010); Johnson et al. (2010)

1.3.2.1 Insolation classification

Cold Jupiter: Jupiter [113]

Jupiter *is Solar System source*

Reason for selection of Jupiter: In Solar System; eponym; atmosphere directly probed

Notes on Jupiter: Radius: 11 $R_\oplus$; mass: 318 $M_\oplus$; insolation: 0.037 Earth; target of *Galileo*, including atmospheric probe

General works about Jupiter: Bolton et al. (2017); Jet Propulsion Laboratory (2020c); Hubbard & Militzer (2016); Seiff et al. (1996)

Relationships between Jupiter and other Exotica Catalog objects: Hosts (is primary of): Amalthea [054], Himalia [056], Europa [104], Callisto [105], Ganymede [106], Io [108], Metis [544]; Orbital primary: Sun [150]

Temperate Jupiter: HD 93083 b [114]

Type references: Schwarz et al. (2007)

HD 93083 b *is sidereal source*

Reason for selection of HD 93083 b: Lowest eccentricity of three candidates in Schwarz et al. (2007)

Notes on HD 93083 b: $M \sin i$: 120 $M_\oplus$; insolation: 1.8 Earth

General works about HD 93083 b: Lovis et al. (2005)

Warm Jupiter: HATS-17 b [115]

HATS-17 b *is sidereal source*

Reason for selection of HATS-17 b: Early discovery, and first detected from ground with low eccentricity

Caveats about selection of HATS-17 b: Density relatively high for giant planet; mass may be dominated by heavy elements

Notes on HATS-17 b: Radius: 8.5 $R_\oplus$; mass: 425 $M_\oplus$; density: 3.5 $\mathrm{g\,cm^{-3}}$; insolation: 72 Earth

Works relating HATS-17 b to type: Brahm et al. (2016)

Hot Jupiter: HD 189733 b [116]

Type references: Hansen & Barman (2007); Fortney et al. (2008)

HD 189733 b *is sidereal source*

Reason for selection of HD 189733 b: Very well-studied; not inflated

Notes on HD 189733 b: Radius: 13 $R_\oplus$; mass: 370 $M_\oplus$; density: 0.86 $\mathrm{g\,cm^{-3}}$; insolation: 330 Earth

Works relating HD 189733 b to type: Bouchy et al. (2005); Knutson et al. (2007)

General works about HD 189733 b: de Kok et al. (2013); Bouchy et al. (2005); Knutson et al. (2007); Evans et al. (2013); Lecavelier Des Etangs et al. (2008)

Works about host of HD 189733 b: Boyajian et al. (2015)

HD 189733 b in I17

1.3.2.2 Radius classifications

Inflated giant planet: HD 209458 b [117]

Type description: Gas giant (frequently a hot Jupiter) with abnormally large radius, often much bigger than Jupiter

Type references: Burrows et al. (2007); Mardling (2007); Batygin & Stevenson (2010); Leconte et al. (2010); Demory & Seager (2011)

HD 209458 b *is sidereal source*

Reason for selection of HD 209458 b: One of first recognized; very well-studied

Notes on HD 209458 b: Radius: 15 $M_\oplus$; mass: 240 $M_\oplus$; density: 0.35 $\mathrm{g\,cm^{-3}}$; insolation: 330 Earth

General works about HD 209458 b: Linsky et al. (2010); Rowe et al. (2006); del Burgo & Allende Prieto (2016)
Works about host of HD 209458 b: Boyajian et al. (2015); del Burgo & Allende Prieto (2016)

Sub-Saturn: Kepler 18 d [118]

Type description: Giant planet with radius between that of Neptune and Saturn ($\sim$ 4–8 $R_\oplus$) and low density, suggesting gas-rich composition ($\sim$ 10–50%); masses range from 6–60 $M_\oplus$; extreme examples with sub-Neptune mass overlap with "super-puff" planets
Type references: Petigura et al. (2017)

Kepler 18 d *is sidereal source*
Reason for selection of Kepler 18 d: One of first examples known with mass comparable to Neptune and far below Saturn; radii and mass known through transits, radial velocities, and transit timing variations
Notes on Kepler 18 d: Radius: 7.0 $R_\oplus$; mass: 16 $M_\oplus$; density: 0.27 $\mathrm{g\,cm^{-3}}$; insolation: 68 Earth
General works about Kepler 18 d: Cochran et al. (2011)

1.3.3 Super-Jovians

Large gas giants that are significantly bigger than Jupiter but below the mass at which deuterium burning occurs. There is no customary lower limit on the mass of super-Jovians: thresholds in the literature include 1 M_J (Clanton & Gaudi 2014), 3 M_J (Johnson et al. 2009), and 5 M_J (Currie et al. 2014). Since many of these planets are detected using the radial velocity method, choosing a planet with $M \sin i \gtrsim 10$ M_J may actually select a brown dwarf. The radial velocity planets we selected have $M \sin i \approx 2$–10 M_J, or true masses in the 3–13 M_J range.

General class also known as: Super-Jupiters

1.3.3.1 Insolation classification

Cold super-Jovian: HR 8799 bcde [119]

Notes on type: Directly imaged planets tend to be cold super-Jovians (Bowler 2016)

HR 8799 bcde *is sidereal source*
Reason for selection of HR 8799 bcde: Well-studied; multiple examples in system
Notes on HR 8799 bcde: All four planets are directly imaged; estimated radii: $\sim$ 13 $R_\oplus$ (b,c,d,e); estimated masses: 1,600–3,500 $M_\oplus$ (b), 2,200–4,100 $M_\oplus$ (c,d), 1,900–4,500 $M_\oplus$ (e); insolation: 0.001 (b), 0.003 (c), 0.009 (d), 0.02 (e)
Works relating HR 8799 bcde to type: Marois et al. (2008, 2010)
General works about HR 8799 bcde: Gravity Collaboration et al. (2019a); Marois et al. (2008, 2010)
HR 8799 bcde in I17

Temperate super-Jovian: HD 28185 b [120]

HD 28185 b *is sidereal source*
Reason for selection of HD 28185 b: Low eccentricity; one of first discovered; listed in Tinney et al. (2011) as possible host of habitable moons
Notes on HD 28185 b: $M \sin i$: 1,800 $M_\oplus$; insolation: 0.96 Earth
Works relating HD 28185 b to type: Santos et al. (2001); Tinney et al. (2011)
General works about HD 28185 b: Tinney et al. (2011); Wittenmyer et al. (2009); Santos et al. (2001)

Warm super-Jovian: HD 80606 b [121]

HD 80606 b *is sidereal source*
Reason for selection of HD 80606 b: Multiple studies; observed in transits
Notes on HD 80606 b: Very high eccentricity ($e = 0.93$); insolation at semimajor axis: 5 Earth
General works about HD 80606 b: Roberts et al. (2013); Hébrard et al. (2010); Moutou et al. (2009)
Works about host of HD 80606 b: Liu et al. (2018)

Hot super-Jovian: HD 147506 b [122]

HD 147506 b *is sidereal source*

HD 147506 b also known as: HAT-P-2b
Reason for selection of HD 147506 b: First transiting hot super-Jovian
Notes on HD 147506 b: Radius: 12 $R_\oplus$; mass: 2,500 $M_\oplus$; density: 12 $\mathrm{g\,cm^{-3}}$; mean insolation: 700 Earth; eccentricity: 0.51
Works relating HD 147506 b to type: Bakos et al. (2007)
General works about HD 147506 b: Bakos et al. (2007); Lewis et al. (2013)

1.3.4 Host classification

Giant planets classified according to the nature of their primary, including binary or evolutionary status.

Giant star host giant planet: Pollux b [123]

Type references: Johnson et al. (2007); Grunblatt et al. (2016)

Pollux b *is sidereal source*
Reason for selection of Pollux b: Explicit prototype; early suspected example; most cited host of Jofré et al. (2015); host in I17
Caveats about selection of Pollux b: Aurière et al. (2014) disputes existence – orbital period similar to host's rotation period, proposes that spots of varying temperature and/or microturbulence are responsible for the signal – but Gray (2014) finds no evidence of temperature variations, and apparently concludes the radial velocity signature indicates a real planet
Notes on Pollux b: Detected by radial velocity method, $M \sin i = 2.3\,\mathrm{M_J} (730\,\mathrm{M_\oplus})$; astrometric constraint on mass: $M < 12.3\,\mathrm{M_J}$; host star in Heiter et al. (2015)
Works where Pollux b referred to as prototype: Aurière et al. (2014)
Works relating Pollux b to type: Larson et al. (1993); Hatzes & Cochran (1993); Hatzes et al. (2006); Aurière et al. (2014)
General works about Pollux b: Reffert & Quirrenbach (2011)
Works about host of Pollux b: Aurière et al. (2009); Gray (2014); O'Gorman et al. (2017)
Pollux b in I17

Alternative prototype(s): Kepler 56 bc: one of the few known such systems with transits, includes a sub-Saturn (22 $M_\oplus$ = 0.070 M_J, 6.5 $R_\oplus$) and gas giant (180 $M_\oplus$ = 0.57 M_J, 9.8 $R_\oplus$) (Huber et al. 2013; Otor et al. 2016) – much further away (940 pc)

White dwarf host giant planet: WD J0914+1914 [079]

Type references: Debes & Sigurdsson (2002)

WD J0914+1914 *is sidereal source*
Reason for selection of WD J0914+1914: Elsewhere in catalog; first likely example – suspected to be a Neptune-mass planet and thus clearly not a brown dwarf
Caveats about selection of WD J0914+1914: Planet possibly tidally disrupted already
Notes on WD J0914+1914: Detected through accretion of material accreted off planet onto white dwarf host
Works relating WD J0914+1914 to type: Gänsicke et al. (2019); Veras & Fuller (2020)
General works about WD J0914+1914: Gänsicke et al. (2019); Veras & Fuller (2020)

Alternative prototype(s): WD 1856+534 b: Jupiter-radius object detected in transit – mass likely < 10 M_J but not confirmed yet (Vanderburg et al. 2020); GJ 3483 B: substellar object in wide orbit around white dwarf host, in superlative catalog – massive, possibly a brown dwarf (Rodriguez et al. 2011)

Neutron star host giant planet: PSR B1620-26 (AB) b [124]

PSR B1620-26 (AB) b *is sidereal source*
Reason for selection of PSR B1620-26 (AB) b: Known likely example, after excluding ablated remnants of companion stars in close orbits around pulsars
Notes on PSR B1620-26 (AB) b: Actually is in orbit of inner neutron star-white dwarf binary; likely entered system through dynamical exchange; located in globular cluster M4
Works relating PSR B1620-26 (AB) b to type: Thorsett et al. (1999); Ford et al. (2000); Sigurdsson & Thorsett (2005)
General works about PSR B1620-26 (AB) b: Sigurdsson & Thorsett (2005)

Circumbinary (non-interacting) giant planet: Kepler 16 b [125]

Type description: Giant planet in wide orbit around close pair of stars that are not interacting
Type references: Holman & Wiegert (1999); Welsh et al. (2012)

Kepler 16 b *is sidereal source*
Reason for selection of Kepler 16 b: First transiting example discovered
Notes on Kepler 16 b: Radius: 8.2 $R_\oplus$; mass: 110 $M_\oplus$; density: 1.0 $\mathrm{g\,cm^{-3}}$; insolation: 0.31 Earth
Works relating Kepler 16 b to type: Doyle et al. (2011); Moorman et al. (2019)

Post common envelope binary giant planet: NN Ser cd [126]

Type description: Giant planets in wide orbit around close binary consisting of hot subdwarf or collapsed star and a companion star
Caveats about type: There have been several claimed planet discoveries around hot subdwarfs based on pulsation timing (e.g., Geier et al. 2009; Charpinet et al. 2011) that have since been discredited (Jacobs et al. 2011; Norris et al. 2011; Krzesinski 2015, e.g.,)
Type references: Bear & Soker (2014); Schleicher & Dreizler (2014); Heber (2016); Pulley et al. (2018)

NN Ser cd *is sidereal source*
Reason for selection of NN Ser cd: Likeliest example to exist – stable if formed after common envelope phase, circumstantial support from dust in system
Caveats about selection of NN Ser cd: How planets could have survived or formed is unclear, leading Mustill et al. (2013) to express doubts about planetary nature; planets may be "second generation", formed after common envelope ejection
Notes on NN Ser cd: Host is close binary of DAO white dwarf and M4 dwarf with orbital period 3.1 hr (Beuermann et al. 2010); planet orbital periods: 7.9 ± 0.5 yr, 15.3 ± 0.3 yr; planet masses: 2.3 ± 0.5 M_J, 7.3 ± 0.5 M_J (Marsh et al. 2014b); cooling age of WD implies planet age of ~ 1 Myr if "second generation"
Works relating NN Ser cd to type: Beuermann et al. (2010); Horner et al. (2012c); Mustill et al. (2013); Marsh et al. (2014b); Parsons et al. (2014); Hardy et al. (2016)

1.3.5 Orbital dynamics classification

Resonant chain (giant) planets: Kepler 223 bcde [127]

Type description: Multiple (giant) planet system in resonance with each other; orbital periods have simple integer ratios
Notes on type: May be a sign of coordinated migration of planets (e.g., Terquem & Papaloizou 2007; Mills et al. 2016)
Type references: MacDonald et al. (2016); Mills et al. (2016); Christiansen et al. (2018); MacDonald & Dawson (2018)

Kepler 223 bcde *is sidereal source*
Reason for selection of Kepler 223 bcde: One of few known examples; ratios extremely close to simple integer ratios; densities indicate all are giants
Notes on Kepler 223 bcde: Ratios of successive periods are 1.333 (4:3, cb), 1.502 (3:2, dc), 1.334 (4:3, ed); planet masses: $7.4^{+1.3}_{-1.1}$ $M_\oplus$ (b), $5.1^{+1.7}_{-1.1}$ $M_\oplus$ (c), $8.0^{+1.5}_{-1.3}$ $M_\oplus$ (d), $4.8^{+1.4}_{-1.2}$ $M_\oplus$ (e); planet radii: $2.99^{+0.18}_{-0.27}$ $R_\oplus$ (b), $3.44^{+0.20}_{-0.30}$ $R_\oplus$ (c), $5.24^{+0.26}_{-0.45}$ $R_\oplus$ (d), $4.60^{+0.27}_{-0.41}$ $R_\oplus$ (e)
Works relating Kepler 223 bcde to type: Mills et al. (2016)

Alternative prototype(s): Kepler-80: nearly contemporaneous discovery, nearer to Earth – period ratios not as simple, planets in three-body resonances (MacDonald et al. 2016); K2-138 bcdef: five planets in resonant chain, each succeeding pair with 3:2 period ratios – planets are smaller (1.6–3.6 $R_\oplus$) (Christiansen et al. 2018); HD 158259 bcdef: five planets in near 3:2 ratios, not as close as Kepler-223 – masses slightly ambiguous in terms of whether actually giant ($M \sin i \sim 5$–7 $M_\oplus$) (Hara et al. 2020)

1.4 Stars

A phylum including protostars, sub-brown dwarfs, brown dwarfs, and the unambiguous stars. They are large (tens of thousands of kilometers or more in radius), in hydrostatic equilibrium, and do not have any solid cores. Nuclear fusion within the interior (either in core or shells) is the main energy source, although gravitational contraction can contribute.

We set the boundaries of this phylum mainly by our sense of convention, although they are not hard and fast. Class 0 (and perhaps Class I) protostars do not have nuclear burning, and could just as well have been placed under the

ISM phylum. Brown dwarfs do burn deuterium briefly, but after that they might be grouped with Giant planets, or even Collapsed stars because they are supported by degeneracy pressure like white dwarfs. On the other hand, white dwarfs (under Collapsed stars) are frequently subjects of stellar population studies and can even have significant though sub-dominant luminosity contributions from nuclear burning. Some suspected remnants of white dwarf-white dwarf mergers (R CrB giants and extreme helium stars) are included in this phylum. Accreting binary systems are placed under Interacting binary stars, even if they have substantial luminosities from fusion like the novae.

Our estimation is that the major distinction between different types of stars is based on evolutionary stage and stellar mass. Brown dwarfs and main sequence (MS) stars are classed by Harvard spectral type. Each spectral type is divided into early (0-3), mid (4-6), and late (7+) subdivisions. Where possible we chose spectral standards as Prototypes (Morgan & Keenan 1973; Kirkpatrick et al. 1991; Garrison 1994; Walborn et al. 2002; Kirkpatrick 2005; Cushing et al. 2005; Burgasser et al. 2006). We also favored stars in I17, because we have already observed a wide range of B through mid-M dwarfs.

Abbreviations for frequently consulted references: MK73: Morgan & Keenan (1973); K91: Kirkpatrick et al. (1991); G94: Garrison (1994); C05: Cushing et al. (2005); H15: Heiter et al. (2015)

1.4.1 Protostars

Pre-stellar gas clouds that are still accreting large amounts of matter onto a central condensation that will become a star. Protostars in their earlier stages have not yet begun hydrogen burning, although determining this in practice can be difficult for young high mass stars, which can accrete and be fusing at the same time (Zinnecker & Yorke 2007).

Low mass protostars and young stars are divided into numerical classes from 0 to III. Classes 2 and 3 are T Tauri pre-main sequence stars with optically thick and optically thin disks, respectively (Lada 1987); only classes 0 and I are generally thought of as proper protostars. High mass protostars are given their own categories.

Class 0 protostar: IRAS 16293-2422 [128]

Type description: Low mass protostar where most mass has not yet condensed; bright submillimeter emission
Type references: Shirley et al. (2002); Froebrich (2005)

IRAS 16293-2422 *is sidereal source*
Reason for selection of IRAS 16293-2422: Explicit prototype; highly cited on Simbad
Works relating IRAS 16293-2422 to type: Bontemps et al. (1996); Ceccarelli et al. (2000); Persson et al. (2018)

Class I protostar: Elias 29 [129]

Type description: Low mass protostar where most mass is centrally concentrated, but still heavily obscured
Type references: van Kempen et al. (2009)

Elias 29 *is sidereal source*
Reason for selection of Elias 29: Highly cited on Simbad
Works relating Elias 29 to type: Boogert et al. (2002); Pillitteri et al. (2019)

High mass protostar: IRAS 20126+4104 [130]

Type description: Protostar that will evolve into star significantly more massive than Sun (Sridharan et al. 2002: $M > 8$ M$_\odot$)
Type references: Sridharan et al. (2002); Motte et al. (2018)

IRAS 20126+4104 *is sidereal source*
Reason for selection of IRAS 20126+4104: Most highly cited of Sridharan et al. (2002) catalog
Notes on IRAS 20126+4104: Mass: ~ 7 M$_\odot$ (Cesaroni et al. 2005), 12 M$_\odot$ (Chen et al. 2016); has disk and jets
Works relating IRAS 20126+4104 to type: Cesaroni et al. (1999, 2005); Chen et al. (2016)

1.4.2 Pre-main sequence stars

Young stars that have begun hydrogen burning but are still contracting on to the main sequence.

T Tauri star: TW Hya [069]

Type description: Low mass pre-main sequence star; surrounded by thick infrared-emitting circumstellar disk; variable;

ages of a few Myr or less
Type references: Bertout (1989); Chiang & Goldreich (1997); Zuckerman & Song (2004)

TW Hya *is sidereal source*
Reason for selection of TW Hya: Nearest example; well-studied; elsewhere in catalog
General works about TW Hya: Andrews et al. (2012); Sokal et al. (2018); Bergin et al. (2013); Andrews et al. (2016b)

Alternative prototype(s): T Tau N: eponym

Herbig Ae/Be star: AB Aur [131]

Type description: Pre-main sequence stars with masses 2–10 $M_{\odot}$, analogous to T Tauri stars; surrounded by infrared-emitting circumstellar disks; ages less than 1 Myr; emission lines from accretion
Type references: The et al. (1994); Waters & Waelkens (1998)

AB Aur *is sidereal source*
Reason for selection of AB Aur: Explicit prototype; well-studied; most citations of Herbig Ae/Be in The et al. (1994) and Herbst & Shevchenko (1999)
Works where AB Aur referred to as prototype: Tannirkulam et al. (2008); Hashimoto et al. (2011)
Works relating AB Aur to type: Tannirkulam et al. (2008)
General works about AB Aur: Tang et al. (2012); Hashimoto et al. (2011)

FU Orionis star: FU Ori [132]

Type description: Protostar or pre-main sequence star undergoing episodes of extreme accretion ($\sim$ 10–100 times normal), resulting in jumps in brightness; appear like yellow supergiants during outburst; subclass of T Tauri stars
Type references: Hartmann & Kenyon (1996)

FU Ori *is sidereal source*
Reason for selection of FU Ori: Eponym and explicit prototype
Notes on FU Ori: Binary disks
Works where FU Ori referred to as prototype: Reipurth & Aspin (2004); Beck & Aspin (2012); Pérez et al. (2020)
General works about FU Ori: Beck & Aspin (2012); Reipurth & Aspin (2004); Pérez et al. (2020)

1.4.3 Sub-brown dwarfs

Sub-brown dwarfs are gaseous bodies that are similar to brown dwarfs, but have too little mass ($\lesssim$ 13 M_J, depending on metallicity; Spiegel et al. 2011) to even burn the majority of their deuterium at any point in their evolution. The applicability of the deuterium burning criterion is disputed (e.g., Spiegel et al. 2011)

The distinction between sub-brown dwarf and super-Jovian planets is blurry, but is one of formation mechanism. The majority opinion is that Super-Jovian planets are formed through core accretion: the building of a solid planetoid in a protoplanetary disk that then becomes encased in an envelope of hydrogen and helium. Sub-brown dwarfs, like brown dwarfs and stars, form from the direct collapse of hydrogen and helium in molecular clouds (Caballero 2018). As a result, super-Jovian planets are typically found orbiting stars (although hypothetically some may end up ejected into interstellar space by gravitational interactions), and sub-brown dwarfs are typically found free-floating in interstellar space (although some may form around stars as a binary companion).

Like main sequence stars and brown dwarfs, sub-brown dwarfs may be classified according to spectral type.

General class also known as: Isolated planetary-mass object (iPMO)
General references: Caballero (2018)

Early Y: WISE J085510.83-071442.5 [133]

WISE J085510.83-071442.5 *is sidereal source*
Reason for selection of WISE J085510.83-071442.5: Elsewhere in catalog; superlative example
Notes on WISE J085510.83-071442.5: Mass: 3–10 M_J; effective temperature: 225–260 K
Works relating WISE J085510.83-071442.5 to type: Luhman (2014); Leggett et al. (2017)
General works about WISE J085510.83-071442.5: Luhman (2014); Skemer et al. (2016)

Relationship to SETI: Y dwarf atmospheres speculated to be habitable (Yates et al. 2017)

1.4.4 Brown dwarfs

Low mass gaseous bodies that form similarly to stars through gravitational collapse; their masses are great enough to burn deuterium ($\gtrsim 13$ M_J), but not enough to burn protium hydrogen ($\lesssim 75$ M_J).

Spectral types are assigned to brown dwarfs. Unlike for main sequence stars, however, the type does not directly map to mass, but are a combination of age and mass, with older and less massive brown dwarfs being colder. The spectral classes L, T, and Y added in the past twenty-five years, corresponding to objects colder than $\sim$ 3,000 K, mostly overlap with brown dwarfs. The smallest stars may have spectral type L and the youngest brown dwarfs have spectral type M, however (Kirkpatrick 2005; Dieterich et al. 2014). The term “ultracool dwarf” refers to objects of late M type or cooler, and is agnostic as to the nature of the objects.

We tried to choose those brown dwarfs with a mass that was clearly below the hydrogen-burning limit.

General references: Basri (2000)

Early Y: WISE J071322.55-291751.9 [134]

WISE J071322.55-291751.9 *is sidereal source*

Reason for selection of WISE J071322.55-291751.9: Most massive (13–29 M_J) Y dwarf in Leggett et al. (2017), above deuterium-burning limit

Late T: 2MASSI J0415195-093506 [135]

2MASSI J0415195-093506 *is sidereal source*

Reason for selection of 2MASSI J0415195-093506: Standard (T8) in Kirkpatrick (2005); Burgasser et al. (2006)

Works where 2MASSI J0415195-093506 referred to as prototype: Kirkpatrick (2005); Burgasser et al. (2006)

Mid T: ϵ Ind Bb [136]

ϵ **Ind Bb** *is sidereal source*

ϵ Ind Bb also known as: ϵ Ind C

Reason for selection of ϵ Ind Bb: Nearby example; in binary, allows more precise mass estimate

Caveats about selection of ϵ Ind Bb: Mass close to hydrogen burning limit at 70 M_J

Notes on ϵ Ind Bb: In multiple system: close binary with ϵ Indi Ba, pair orbits ϵ Indi A; spectral type: T6

Works relating ϵ Ind Bb to type: McCaughrean et al. (2004)

General works about ϵ Ind Bb: Dieterich et al. (2018)

Relationships between ϵ Ind Bb and objects in I17: Gravitationally bound to: GJ845A

Early T: Luhman 16B [137]

Luhman 16B *is sidereal source*

Reason for selection of Luhman 16B: Nearest example; in binary with late L prototype

Notes on Luhman 16B: Spectral classification: T0.5

Works relating Luhman 16B to type: Burgasser et al. (2013)

General works about Luhman 16B: Lazorenko & Sahlmann (2018); Luhman (2013)

Relationships between Luhman 16B and other Exotica Catalog objects: Within the sky region occupied by: Luhman 16 [323]; Is mutually orbiting: Luhman 16B [137]

Late L: Luhman 16A [138]

Luhman 16A *is sidereal source*

Reason for selection of Luhman 16A: Nearest example; in binary with early T prototype

Notes on Luhman 16A: Spectral classification: L7.5

Works relating Luhman 16A to type: Burgasser et al. (2013)

General works about Luhman 16A: Lazorenko & Sahlmann (2018); Luhman (2013)

Relationships between Luhman 16A and other Exotica Catalog objects: Within the sky region occupied by: Luhman 16 [323]; Is mutually orbiting: Luhman 16A [138]

Mid L: HD 130948BC [139]

HD 130948BC *is sidereal source*
Reason for selection of HD 130948BC: Benchmark according to Dupuy et al. (2009)
Notes on HD 130948BC: Binary of two L4 brown dwarfs, total mass 115 M_J (thus one has mass $\leq$ 58 M_J)
Works where HD 130948BC referred to as prototype: Dupuy et al. (2009)
General works about HD 130948BC: Dupuy et al. (2009); Dupuy & Liu (2017)
HD 130948BC in I17

Early L: 2MASSI J1506544+132106 [140]

2MASSI J1506544+132106 *is sidereal source*
Reason for selection of 2MASSI J1506544+132106: L3V standard in C05, Cruz et al. (2018)
Caveats about selection of 2MASSI J1506544+132106: Mass not measured; could be very low mass star
Works where 2MASSI J1506544+132106 referred to as prototype: Cushing et al. (2005); Cruz et al. (2018)

M: PPL 15 [141]

PPL 15 *is sidereal source*
Reason for selection of PPL 15: Early discovery
Notes on PPL 15: Spectral classification: M6.5
General works about PPL 15: Basri & Martín (1999); Bihain et al. (2010)

1.4.5 Main sequence stars

Stars that are fusing hydrogen in their cores, falling on a well-defined locus in the Hertzprung-Russel diagram from faint and red to bright and blue. Surface temperature and spectral class are closely related to stellar mass: low mass MS stars are red and late type, high mass MS stars are blue and early type. We therefore use spectral classes to sample the sequence.

Abbreviation for general class: MS
General class also known as: Dwarf stars

Early L: 2MASS J0523-1403 [142]

2MASS J0523-1403 *is sidereal source*
Reason for selection of 2MASS J0523-1403: Determined by Dieterich et al. (2014) to be star and not brown dwarf; elsewhere in catalog
Notes on 2MASS J0523-1403: Spectral classification: L2.5V
Works relating 2MASS J0523-1403 to type: Dieterich et al. (2014)
General works about 2MASS J0523-1403: Dieterich et al. (2014)

Late M: VB 10 [143]

VB 10 *is sidereal source*
VB 10 also known as: Gl 752 B
Reason for selection of VB 10: K91, C05: M8V standard; well-cited; seems to fall along stellar sequence in Dieterich et al. (2014)
Notes on VB 10: Lowest mass star known for decades (Caballero 2018)
Works where VB 10 referred to as prototype: Kirkpatrick et al. (1991); Cushing et al. (2005)

Mid M: Wolf 359 [144]

Wolf 359 *is sidereal source*
Wolf 359 also known as: GJ 406
Reason for selection of Wolf 359: K91, C05: M6V primary standard; well-cited; in I17; one of nearest stars

Works where Wolf 359 referred to as prototype: Kirkpatrick et al. (1991); Cushing et al. (2005)
Wolf 359 in I17

Early M: HD 95735 [145]

HD 95735 *is sidereal source*
HD 95735 also known as: GJ 411
Reason for selection of HD 95735: K91,C05: M2V primary standard; well-cited; in I17
Works where HD 95735 referred to as prototype: Kirkpatrick et al. (1991); Cushing et al. (2005)
HD 95735 in I17

Late K: 61 Cyg B [146]

61 Cyg B *is sidereal source*
Reason for selection of 61 Cyg B: MK73, K91: K7V standard; most well-cited example within 30 pc; in I17
Works where 61 Cyg B referred to as prototype: Morgan & Keenan (1973); Kirkpatrick et al. (1991)
61 Cyg B in I17
Relationships between 61 Cyg B and other Exotica Catalog objects: Is mutually orbiting: 61 Cyg A [147]

Mid K: 61 Cyg A [147]

61 Cyg A *is sidereal source*
Reason for selection of 61 Cyg A: MK73, K91, G94: K5V standard; most well-cited example within 30 pc; in I17
Works where 61 Cyg A referred to as prototype: Morgan & Keenan (1973); Kirkpatrick et al. (1991); Garrison (1994)
61 Cyg A in I17
Relationships between 61 Cyg A and other Exotica Catalog objects: Is mutually orbiting: 61 Cyg B [146]

Early K: ϵ Eri [148]

ϵ **Eri** *is sidereal source*
Reason for selection of ϵ Eri: Nearby star; "anchor point" in MK system (G94); well-studied; in I17
Works where ϵ Eri referred to as prototype: Garrison (1994)
ϵ Eri in I17

Late G: τ Cet [072]

τ **Cet** *is sidereal source*
Reason for selection of τ Cet: Nearby star; well-studied; in I17
General works about τ Cet: di Folco et al. (2007); MacGregor et al. (2016); Greaves et al. (2004)
τ Cet in I17

Mid G: κ_1 Cet [149]

κ_1 **Cet** *is sidereal source*
Reason for selection of κ_1 Cet: Highly cited; "anchor point" in MK system (G94); elsewhere in catalog; in I17
Notes on κ_1 Cet: Superflare star (Schaefer et al. 2000)
Works where κ_1 Cet referred to as prototype: Garrison (1994)
General works about κ_1 Cet: Lynch et al. (2019); do Nascimento et al. (2016); Ribas et al. (2010)
κ_1 Cet in I17

Early G: Sun [150]

Sun *is Solar System source*
Reason for selection of Sun: MK73, G94: G2V standard; very nearby
Works where Sun referred to as prototype: Morgan & Keenan (1973); Garrison (1994)
Relationships between Sun and other Exotica Catalog objects: Hosts (is primary of): 446 Aeternitas [001], 52 Europa [002], 624 Hektor [003], 434 Hungaria [004], 16 Psyche [005], 3628 Božněmcová [006], 420 Bertholda [007], 1862 Apollo [008], 349

Dembowska [009], 15 Eunomia [010], 233 Asterope [011], 4 Vesta [012], 90 Antiope [013], 3200 Phaethon [015], 2020 AV_2 [016], (322756) 2001 CK_{32} [017], 163693 Atira [018], 3753 Cruithne [019], 1991 VG [020], 2010 TK_7 [021], (469219) Kamo'oalewa [022], 4660 Nereus [023], 433 Eros [024], 5261 Eureka [025], 8 Flora [026], 25 Phocaea [027], 65 Cybele [028], 153 Hilda [029], 6P/d'Arrest [030], 21P/Giacobini-Zinner [031], 1P/Halley [032], C/2014 S3 (PAN-STARRS) [033], 5335 Damocles [034], 2P/Encke [036], 133P/Elst-Pizarro [037], 9P/Tempel 1 [038], 2060 Chiron [039], 153P/Ikeya-Zhang [040], (24835) 1995 SM_{55} [041], (15788) 1993 SB [042], (385185) 1993 RO [043], 15760 Albion [044], 79360 Sila-Nunam [045], 2011 QF_{99} [046], 2001 QR_{322} [047], (523899) 1997 CV_{29} [048], (20161) 1996 TR_{66} [049], (91554) 1999 RZ_{215} [050], (181902) 1999 RD_{215} [051], 541132 Leleākūhonua [052], 2006 RH_{120} [060], Saturn [064], Neptune [065], Mercury [080], Mars [082], Venus [085], 1 Ceres [095], 136199 Eris [096], 134340 Pluto [097], 90377 Sedna [098], 136472 Makemake [099], 136108 Haumea [100], Jupiter [113], Tesla Roadster [532], Earth-Sun L_4 [535], 1173 Anchises [537], (55636) 2002 TX_{300} [538], 2019 LF_6 [540], 2012 VP_{113} [541], 17P/Holmes [675], Uranus [676], (10537) 1991 RY_{16} [695]; Opposite point on sky from: Solar antipoint [533]

Late F: β Vir [151]

β **Vir** *is sidereal source*
β Vir also known as: Zavijava
Reason for selection of β Vir: MK73: F9V standard; second most cited within 30 pc on Simbad; in I17
Works where β Vir referred to as prototype: Morgan & Keenan (1973)
β Vir in I17

Mid F: π_3 Ori [152]

π_3 **Ori** *is sidereal source*
π_3 Ori also known as: Tabit
Reason for selection of π_3 Ori: MK73, G94: F6V standard; second most cited within 30 pc on Simbad; in I17
Works where π_3 Ori referred to as prototype: Morgan & Keenan (1973); Garrison (1994)
π_3 Ori in I17

Early F: 78 UMa [153]

78 UMa *is sidereal source*
Reason for selection of 78 UMa: MK73, G94: F2V standard; in I17
Works where 78 UMa referred to as prototype: Morgan & Keenan (1973); Garrison (1994)
78 UMa in I17

Late A: α Cep [154]

Notes on type: No MK73 standard

α **Cep** *is sidereal source*
α Cep also known as: Alderamin
Reason for selection of α Cep: Highly cited; not peculiar nor possibly subgiant; in I17
α Cep in I17

Mid A: Alcor [155]

Notes on type: No MK73 standard

Alcor *is sidereal source*
Alcor also known as: g UMa
Reason for selection of Alcor: Highly cited; in I17
Alcor in I17

Early A: Vega [156]

Vega *is sidereal source*
Vega also known as: α Lyr

Reason for selection of Vega: MK73, G94: A0V standard; well-studied; ultimate calibrator of Vega magnitude system; in I17
Vega in I17

Late B: λ Aql [157]

λ **Aql** *is sidereal source*
Reason for selection of λ Aql: One of few in I17, second most-cited after Algol (an interacting binary)
λ Aql in I17

Mid B: α Gru [158]

α **Gru** *is sidereal source*
α Gru also known as: Alnair
Reason for selection of α Gru: Only example in I17; well-cited
α Gru in I17

Early B: η UMa [159]

η **UMa** *is sidereal source*
η UMa also known as: Alkaid
Reason for selection of η UMa: MK73, G94: B3V standard; highly-cited; in I17
Works where η UMa referred to as prototype: Morgan & Keenan (1973); Garrison (1994)
η UMa in I17

Late O: 10 Lac [160]

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10 Lac *is sidereal source*
10 Lac also known as: HIP 11841
Reason for selection of 10 Lac: MK73, G94: O9V standard
Works where 10 Lac referred to as prototype: Morgan & Keenan (1973); Garrison (1994)

Mid O: HD 46150 [161]

HD 46150 *is sidereal source*
Reason for selection of HD 46150: MK73, Walborn et al. (2002): O5V standard
Notes on HD 46150: Located in star cluster NGC 2244, within middle of Rosette Nebula
Works where HD 46150 referred to as prototype: Morgan & Keenan (1973); Walborn et al. (2002)

Early O: HD 64568 [162]

HD 64568 *is sidereal source*
Reason for selection of HD 64568: Walborn et al. (2002): O3V standard
Works where HD 64568 referred to as prototype: Morgan & Keenan (1973); Walborn et al. (2002)

1.4.6 Post main sequence stars

The post main-sequence evolution of stars is complex and diverse, and each mass range leading to unique phenomena. Stars that are actually in distinct evolutionary stages can appear on the same place in the HR diagram, such as the red giant branch and the asymptotic giant branch. We group stars by these mass ranges, and then list discernible stages within. ETIs living around stars in different groups would face different challenges when adapting to post-MS evolution (for example, the post-helium flash contraction would require large-scale migration over just a few millennia to remain in the habitable zone). For low- and intermediate-mass stars, we preferred to use *Gaia* benchmark stars with well-determined masses (Heiter et al. 2015).

1.4.6.1 Very low mass stars

These have initial masses $\lesssim 0.2\ M_\odot$ and remain fully convective through their entire MS lifetime. They are expected not to have a distinct red giant phase, instead growing bluer and brighter before fading into white dwarfs (Laughlin et al. 1997). The Universe is not old enough for any isolated very low mass stars to reach post-MS stages.

1.4.6.2 Low mass stars

Stars with initial masses of 0.2–2.2 $M_\odot$. Post-MS evolution is characterized by 1.) a prolonged subgiant phase, 2.) an ascent up the red giant branch (RGB) terminated by a helium flash in a degenerate core, 3.) rapid settling into a core helium burning (CHeB) phase, 4.) ascent up the asymptotic giant branch (AGB) that builds a carbon-oxygen (CO) core. The ultimate product is a CO white dwarf. The upper limit of 2.2 $M_\odot$ is the maximum initial stellar mass for which a helium flash occurs.

1.4.6.2.1 Subgiants

Subgiants have turned off the main sequence, with their core hydrogen exhausted. They are still building convective envelopes, maintaining roughly constant luminosities but swelling in radius and dropping in surface temperature.

K subgiant: κ CrB [163]

κ **CrB** *is sidereal source*
Reason for selection of κ CrB: MK73: K1 IV standard; well-studied; in I17
Notes on κ CrB: Mass: 1.5 $M_\odot$; known exoplanet host
Works where κ CrB referred to as prototype: Morgan & Keenan (1973)
General works about κ CrB: Baines et al. (2013)
κ CrB in I17

G subgiant: μ Her [164]

μ **Her** *is sidereal source*
Reason for selection of μ Her: MK73, G94: G5 IV standard; well-studied
Notes on μ Her: Mass: 1.1 $M_\odot$
Works where μ Her referred to as prototype: Morgan & Keenan (1973); Garrison (1994)
Works relating μ Her to type: Li et al. (2019)
μ Her in I17

F subgiant: Procyon A [165]

Procyon A *is sidereal source*
Procyon A also known as: α CMi A
Reason for selection of Procyon A: Very well studied; H15 *Gaia* benchmark; in I17
Caveats about selection of Procyon A: Transitioning between MS and subgiant phase, H15 places it as dwarf – Bond et al. (2015) calls it a "slightly evolved subgiant"
Notes on Procyon A: Spectral classification: F5 IV-V; mass: 1.48 ± 0.01 $M_\odot$
Works where Procyon A referred to as prototype: Heiter et al. (2015)
General works about Procyon A: Heiter et al. (2015); Bond et al. (2015)
Procyon A in I17

A subgiant: ι UMa [166]

ι **UMa** *is sidereal source*
ι UMa also known as: Talitha
Reason for selection of ι UMa: MK73: A7 IV standard; well-studied; in I17
Caveats about selection of ι UMa: Zhuchkov et al. (2012) lists spectral type as F0 IV-V
Notes on ι UMa: Mass: 1.75 $M_\odot$; part of a quadruple system
Works where ι UMa referred to as prototype: Morgan & Keenan (1973)
General works about ι UMa: Zhuchkov et al. (2012); David & Hillenbrand (2015)
ι UMa in I17

1.4.6.2.2 Low mass RGB

Red giants stars burning hydrogen in a shell around a degenerate helium core, with convective envelopes. As shell burning proceeds, they grow brighter and cooler. This phase ends with a helium flash in which a large fraction of the degenerate core undergoes fusion into carbon.

M giant: γ Cru [167]

γ **Cru** *is sidereal source*
γ Cru also known as: Gacrux
Reason for selection of γ Cru: Coolest giant in I17; well-studied; representative for M giants in Carpenter et al. (2018)
Caveats about selection of γ Cru: Eggen (1992) lists as AGB
Notes on γ Cru: Mass: 1.5 ± 0.3 $M_\odot$ (Ohnaka 2014)
Works relating γ Cru to type: Ohnaka (2014); Carpenter et al. (2018)
γ Cru in I17

Late K giant: Aldebaran [168]

Aldebaran *is sidereal source*
Aldebaran also known as: α Tau
Reason for selection of Aldebaran: H15 benchmark; well-studied; in I17
Notes on Aldebaran: Mass: 0.96 $M_\odot$
Works where Aldebaran referred to as prototype: Heiter et al. (2015)
General works about Aldebaran: Heiter et al. (2015)
Aldebaran in I17

Early K giant: Arcturus [169]

Arcturus *is sidereal source*
Arcturus also known as: α Boo
Reason for selection of Arcturus: H15 benchmark; most cited red giant in I17; closest red giant
Notes on Arcturus: Mass: 1.03 $M_\odot$
Works where Arcturus referred to as prototype: Heiter et al. (2015)
General works about Arcturus: Heiter et al. (2015)
Arcturus in I17

1.4.6.2.3 Low mass CHeB

Stage of stellar evolution in which helium is burning in the core of the star, within a hydrogen burning shell. These stars are part way up the RGB in terms of luminosity, and either slightly or much bluer.

Sometimes all CHeB stars are called “horizontal branch” (HB), but this usage is fading.

Low mass red clump star: α Ser [170]

Type description: High-metallicity (including Solar metallicity) low mass CHeB star; all have similar luminosities and temperatures, resulting in cluster in H-R diagram close to the RGB
Type references: Girardi (2016)

α **Ser** *is sidereal source*
α Ser also known as: Unukalhai
Reason for selection of α Ser: Most highly cited of red clump stars in Liu et al. (2007); highly cited; typical example (Gray 2016); in I17
Notes on α Ser: Mass estimates of 0.95–1.8 $M_\odot$, Gray (2016) adopt 1.6 $M_\odot$
General works about α Ser: Gray (2016)
α Ser in I17

Low mass red horizontal branch star: BD +17 3248 [171]

Type description: Low-metallicity low mass CHeB star; hotter than RGB, cooler than instability strip

BD +17 3248 *is sidereal source*
Reason for selection of BD +17 3248: Most cited red HB star within 1 kpc in Simbad with $[Fe/H] < -0.3$; explicitly a red HB in Dupree et al. (2009); For & Sneden (2010)

Works relating BD +17 3248 to type: Behr (2003); For & Sneden (2010)
General works about BD +17 3248: For & Sneden (2010); Behr (2003)

Low mass RR Lyrae: RR Lyr [172]

Type description: Low-metallicity low mass CHeB star; temperature places it on instability strip in HR diagram; variable
Relationship with other types: Stars in this part of the HR diagram are RR Lyrae variables

RR Lyr *is sidereal source*
Reason for selection of RR Lyr: Eponym of variable star class; elsewhere in catalog
General works about RR Lyr: Benedict et al. (2011)

Low mass blue horizontal branch star: HD 161817 [173]

Type description: Low-metallicity low mass CHeB star; hotter than instability strip; spectral types B–A
Caveats about type: May be product of binary evolution, like extreme horizontal branch stars (Heber 2016)

HD 161817 *is sidereal source*
Reason for selection of HD 161817: Most cited HB star within 1 kpc in Simbad with $[Fe/H] < -0.3$; explicitly blue HB in For & Sneden (2010)
Works relating HD 161817 to type: Behr (2003); For & Sneden (2010)

1.4.6.2.4 Low–intermediate mass AGB

Low and intermediate mass stars that have exhausted core helium and are now burning hydrogen and helium in concentric shells. The core is degenerate carbon and oxygen. These stars climb the AGB, becoming brighter and redder. On the HR diagram, the AGB and RGB overlap. Thermal pulses are unique to late AGB evolution. The envelope is ejected at the end of the AGB phase.

Initial masses are rarely specified, thus the low and intermediate mass AGB stars are lumped together.

M giant: R Dor [174]

R Dor *is sidereal source*
Reason for selection of R Dor: Nearest example; highly-cited
Notes on R Dor: Initial mass: 1–1.25 $M_\odot$; mass: 0.7–1 $M_\odot$
Works relating R Dor to type: Ohnaka et al. (2019)

S (intrinsic) giant: RS Cnc [175]

Type description: AGB star where s-process elements formed in interior have been brought up to surface by convective envelope; atmospheres enriched in oxygen relative to carbon; includes technetium stars

RS Cnc *is sidereal source*
Reason for selection of RS Cnc: Third closest and second-most cited in Simbad; has Tc in spectrum; not polluted by companion
Notes on RS Cnc: Initial mass: 1.5 $M_\odot$, mass: 1.2 $M_\odot$ (from Libert et al. 2010)
Works relating RS Cnc to type: Libert et al. (2010)
General works about RS Cnc: Lebzelter & Hron (1999); Libert et al. (2010)

C giant: IRC +10216 [176]

Type description: AGB star with carbon-enriched (relative to oxygen) atmosphere; generally occurs for stars with initial masses above 1.5 $M_\odot$ (van Winckel 2003); luminosity limited by hot bottom burning (Boothroyd et al. 1993); strong mass loss; infrared bright

IRC +10216 *is sidereal source*
IRC +10216 also known as: CW Leo
Reason for selection of IRC +10216: Well-studied example; one of the "best studied" according to Males et al. (2012)
Notes on IRC +10216: Initial mass: 3–5 $M_\odot$, current mass: 0.8 ± 0.1 $M_\odot$ (Matthews et al. 2015, and references therein); transitioning from AGB to post-AGB

Works relating IRC +10216 to type: Miller (1970); Males et al. (2012); Matthews et al. (2015)
General works about IRC +10216: Matthews et al. (2015); Becklin et al. (1969); Males et al. (2012)

OH/IR giant: IRC +10011 [177]

Type description: AGB star with oxygen-enriched envelope, resulting in OH maser emission; enrichment from hot bottom burning in which CNO cycle of hydrogen burning proceeds at base of convective envelope (Slemer et al. 2017); initial mass > 4 $M_\odot$; infrared bright
Type references: Lewis (2002); Goldman et al. (2018)

IRC +10011 *is sidereal source*
IRC +10011 also known as: WX Psc
Reason for selection of IRC +10011: Among sample of Wilson et al. (1970); one of most cited in Gaylard et al. (1989); Lewis et al. (2004)
Works relating IRC +10011 to type: Orosz et al. (2017)
General works about IRC +10011: Orosz et al. (2017); Engels et al. (2015)

1.4.6.2.5 Low–intermediate mass post-AGB stars

Stars that are moving from the tip of the AGB to much hotter temperatures as they eject their envelope, ultimately on their way to the white dwarf sequence. In some cases, they can re-initiate fusion for a short while.

Post-AGB star: HD 44179 [178]

Type description: Has ejected much of its envelope into a "proto-planetary nebula", which is not yet ionized
Type references: van Winckel (2003)

HD 44179 *is sidereal source*
Reason for selection of HD 44179: Possible prototype; very well studied; elsewhere in catalog
Notes on HD 44179: Often regarded as intermediate mass (Witt et al. 2009); Men'shchikov et al. (2002) proposes binary evolution scenario with post-AGB initial mass 1.5–1.9 $M_\odot$
Works where HD 44179 referred to as prototype: Witt et al. (2009)
General works about HD 44179: Witt et al. (2009); Men'shchikov et al. (2002)
Relationships between HD 44179 and other Exotica Catalog objects: Within the sky region occupied by: Red Rectangle nebula [364]

Final flash star: V4334 Sgr [179]

Type also known as: Born again giant
Type description: Star undergoing helium flash in a shell after leaving AGB; backtracks to AGB briefly before resuming track towards hotter temperatures; very short lived phase, evolution over years
Relationship with other types: Can briefly appear to be R CrB star (in abundance and variability), which they have been proposed to be related to, but so far this similarity has only been proposed to last for a few years (Asplund et al. 1999; Clayton et al. 2006)
Type references: Clayton & De Marco (1997); van Winckel (2003); Clayton et al. (2006)

V4334 Sgr *is sidereal source*
V4334 Sgr also known as: Sakurai's Object
Reason for selection of V4334 Sgr: Famous example, one of few known; relatively recent outburst
Notes on V4334 Sgr: Initial mass: 2.5 $M_\odot$
Works relating V4334 Sgr to type: Duerbeck & Benetti (1996); Duerbeck et al. (1997); Asplund et al. (1999)
General works about V4334 Sgr: Hinkle & Joyce (2014)

1.4.6.3 Intermediate mass stars

In this work, stars with initial mass 2.2–7 $M_\odot$. Post-MS evolution is characterized by 1.) a rapid crossing of the "Hertzprung gap" as a subgiant, 2.) an ascent up the RGB with a non-degenerate helium core, 3.) gradual core helium burning onset leading into a CHeB phase, which may include a "blue loop" on the HR diagram. From then on, they ascend up the AGB with a degenerate CO core and end as a CO white dwarf like low mass stars, although elemental abundances can vary as an AGB.

In the literature, "intermediate" mass includes heavier stars that do not have a core collapse supernova (see transitional mass stars). What we call "intermediate", Karakas & Lattanzio (2014) refers to as "lower intermediate".

See under "low mass stars" for intermediate mass AGB and post-AGB stars.

1.4.6.3.1 Intermediate mass subgiants

B subgiant: Regulus [180]

Regulus *is sidereal source*
Regulus also known as: α Leo
Reason for selection of Regulus: Only non-peculiar B subgiant in I17
Caveats about selection of Regulus: Che et al. (2011) classes Regulus as a dwarf
Notes on Regulus: Mass: 3.8 $M_\odot$ (Hadjara et al. 2018); spectral type: B8 IVn (Gray et al. 2003)
General works about Regulus: Hadjara et al. (2018)
Regulus in I17

Hertzprung gap subgiant: Capella Ab [181]

Type description: Intermediate mass star in brief transition phase onto red giant branch; spectral types of F through mid G
Type references: Ayres et al. (1998)

Capella Ab *is sidereal source*
Capella Ab also known as: α Aur Ab
Reason for selection of Capella Ab: Nearest example; well studied; well characterized as member of binary, including mass; companion elsewhere in catalog
Notes on Capella Ab: Mass: 2.48 $M_\odot$; radius: 8.83 $R_\odot$; luminosity: 72.7 $L_\odot$; effective temperature: 5,730 K
General works about Capella Ab: Torres et al. (2015)
Relationships between Capella Ab and other Exotica Catalog objects: Is mutually orbiting: Capella Aa [186]

Alternative prototype(s): 31 Com: explicitly described as "archetypal Hertzprung hap" by Scelsi et al. (2004) – more distant, not as well characterized

1.4.6.3.2 Intermediate mass RGB

K giant: α Hya [182]

α **Hya** *is sidereal source*
α *Hya also known as:* Alphard
Reason for selection of α *Hya:* MK73: K3 II-III standard; most cited K giant of da Silva et al. (2006)
Notes on α *Hya:* Mass: 3.0 ± 0.4 $M_\odot$
Works where α *Hya referred to as prototype:* Morgan & Keenan (1973)
General works about α *Hya:* da Silva et al. (2006)

M giant: α Cet [183]

α **Cet** *is sidereal source*
α *Cet also known as:* Menkar
Reason for selection of α *Cet:* MK73: M1.5 III standard; third most cited giant in Halabi & Eid (2015)
Notes on α *Cet:* Initial mass: 3.0 $M_\odot$; mass: 2.3 $M_\odot$ (Wittkowski et al. 2006, dependent on evolutionary tracks), 2.9 $M_\odot$ (Halabi & Eid 2015)
Works where α *Cet referred to as prototype:* Morgan & Keenan (1973)
General works about α *Cet:* Halabi & Eid (2015); Wittkowski et al. (2006)

1.4.6.3.3 Intermediate mass giants

Intermediate stars where it is not clear whether they are on the RGB, CHeB, or AGB; selected for spectral type coverage.

K supergiant: ζ Aur [184]

ζ **Aur** *is sidereal source*
Reason for selection of ζ Aur: To increase sampling of HR diagram
Notes on ζ Aur: Mass: 5.8 ± 0.2 $M_\odot$; spectral type: K4 Ib
General works about ζ Aur: Bennett et al. (1996)

G giant: ϵ Vir [185]

ϵ **Vir** *is sidereal source*
ϵ Vir also known as: Vindemiatrix
Reason for selection of ϵ Vir: MK73: G8 IIIab standard; G94: G8 III anchor point in MK system; H15 benchmark; very well-studied
Notes on ϵ Vir: Mass: 2.4–3.0 $M_\odot$; considered by Stock et al. (2018); Howes et al. (2019) to be almost certainly a red clump star; Sahlholdt et al. (2019) considers it to be RGB
Works where ϵ Vir referred to as prototype: Morgan & Keenan (1973); Garrison (1994); Heiter et al. (2015)
Works relating ϵ Vir to type: Gray (2017)
General works about ϵ Vir: Stock et al. (2018); Sahlholdt et al. (2019); Howes et al. (2019); Heiter et al. (2015); Gray (2017)
ϵ Vir in I17

1.4.6.3.4 Intermediate mass CHeB

Intermediate mass red clump star: Capella Aa [186]

Type description: High-metallicity (including Solar metallicity) intermediate mass CHeB star with initial mass $\lesssim 5$ $M_\odot$; cluster in H-R diagram close to the RGB

Capella Aa *is sidereal source*
Capella Aa also known as: α Aur Aa
Reason for selection of Capella Aa: One of nearest giants; very well-studied and well-characterized; companion elsewhere in catalog
Notes on Capella Aa: In multiple system; close binary with slightly less massive Capella Ab; mass: 2.6–2.7 $M_\odot$
General works about Capella Aa: Sablowski et al. (2019); Torres et al. (2015); Takeda et al. (2018)
Relationships between Capella Aa and other Exotica Catalog objects: Is mutually orbiting: Capella Ab [181]

Blue loop star: δ Cep [187]

Type description: Intermediate mass CHeB star with initial mass $\gtrsim$ 3–5 $M_\odot$; slowly arcs away and towards RGB on HR diagram
Type references: Walmswell et al. (2015)

δ **Cep** *is sidereal source*
Reason for selection of δ Cep: Highly cited; elsewhere in catalog
General works about δ Cep: Natale et al. (2008); Matthews et al. (2012)

Classical Cepheid variable star: δ Cep [187]

Type description: High-metallicity intermediate mass CHeB star, crossing instability strip during blue loop; generally supergiants
Type references: Monson et al. (2012)

δ **Cep** *is sidereal source*
Reason for selection of δ Cep: Eponym; highly cited; elsewhere in catalog
Notes on δ Cep: Initial mass: 5.5 $M_\odot$; mass measured with pulsations: 4.5 $M_\odot$; discrepant masses characteristic of Cepheids (Cox 1980)
Works relating δ Cep to type: Natale et al. (2008)
General works about δ Cep: Natale et al. (2008); Matthews et al. (2012)

1.4.6.4 Transitional mass stars

In this work, stars with initial mass $\sim$ 7–11 $M_\odot$ that share some evolutionary features of both low/intermediate mass stars and massive stars. Their evolution to the AGB stage is similar to the intermediate-mass stars. However, at the AGB phase, they continue to evolve by 1.) initiating carbon burning in a nondegenerate carbon core and 2.) entering a super AGB phase with hydrogen, helium, and carbon shell burning around an oxygen-neon-magnesium (ONeMg) core. Those with lower masses eject their envelopes, leaving a massive ONeMg white dwarf (Karakas & Lattanzio 2014; Doherty et al. 2017). Those with higher masses are thought to undergo an electron capture supernova (ECSN), which may result in a white dwarf or neutron star (Woosley & Heger 2015; Jones et al. 2016b). Karakas & Lattanzio (2014) refers to the former as "middle intermediate" mass and the latter as "high intermediate mass". The mass ranges are too narrow, too metallicity dependent, and too simulation-dependent to sort observed transitional mass stars into these categories. Improvements in theory and empirical mass determinations may allow for this separation in future versions of the catalog.

The term "transitional mass" does not appear in the literature; we use it to emphasize the different evolutionary paths of these stars.

K supergiant: β Ara [188]

β **Ara** *is sidereal source*
Reason for selection of β *Ara:* H15 benchmark; fairly well studied
Notes on β *Ara:* Mass: 8.22 ± 1.88 $M_\odot$; spectral classification: K3 Ib-II
General works about β *Ara:* Heiter et al. (2015)

G supergiant: l Car [189]

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l Car *is sidereal source*
Reason for selection of l Car: Nearby example; well-studied
Notes on l Car: Mass: $8.66 \pm 0.14 M_\odot$; closest long-period Cepheid variable (in instability strip); likely on blue loop
General works about l Car: Neilson et al. (2016)

AF supergiant: Canopus [190]

Canopus *is sidereal source*
Canopus also known as: α Car
Reason for selection of Canopus: Second brightest exo-star in sky; well-studied
Notes on Canopus: Initial mass: 8 ± 0.3 $M_\odot$; spectral classification: F0 II; may be in blue loop phase
General works about Canopus: Cruzalèbes et al. (2013); Domiciano de Souza et al. (2008)

Super-AGB star: MSX SMC 055 [191]

Notes on type: Transitional mass star with carbon shell burning around ONeMg core; difficult to tell apart from red supergiants
Type references: Doherty et al. (2017)

MSX SMC 055 *is sidereal source*
Reason for selection of MSX SMC 055: Likeliest example
Notes on MSX SMC 055: Current mass: 8.5 ± 1.6 $M_\odot$
Works relating MSX SMC 055 to type: Groenewegen & Sloan (2018)
Works about host of MSX SMC 055: Scowcroft et al. (2016)
Relationships between MSX SMC 055 and objects in I17: Within the sky region occupied by: SMC

1.4.6.5 Massive stars

Stars with initial masses in the range $\sim$ 11–40 $M_\odot$. These stars's post-MS evolution involves the full sequence of nuclear burning through oxygen, neon, silicon, and iron, with an onion-like structure. The late stages of nuclear evolution happen rapidly due to neutrino energy losses. Observationally, they 1.) move off the blue main sequence while remaining bright, becoming red supergiants, 2.) swing back and forth between red supergiant and blue supergiant phases, and 3.) if they have initial masses 30–40 $M_\odot$, experience severe mass loss that exposes a Wolf-Rayet star

(Clark et al. 2012). Evolution terminates with a core collapse, followed by either a core collapse supernova or a "failed" supernova, leaving behind a neutron star or black hole.

1.4.6.5.1 Giants

OB giant: ι Ori AB [192]

ι **Ori AB** *is sidereal source*
Reason for selection of ι Ori AB: MK73: O9 III standard; highly-cited; binary has both O and B giants
Notes on ι Ori AB: Mass: 23.2 ± 0.6 $M_\odot$ (A), 13.4 ± 0.4 $M_\odot$ (B); spectral classification: O9 III (A), B1 III-IV (B)
Works where ι Ori AB referred to as prototype: Morgan & Keenan (1973)
General works about ι Ori AB: Pablo et al. (2017)
Relationships between ι Ori AB and other Exotica Catalog objects: Within the sky region occupied by: Orion A [351]; Adjacent on sky to (sharing parent object with): M42 [357]

1.4.6.5.2 Supergiants and hypergiants

Blue (B) supergiant: ζ Per [193]

ζ **Per** *is sidereal source*
Reason for selection of ζ Per: MK73: B1 Ib standard; highly-cited, although mostly for studies of ISM on sightline
Notes on ζ Per: Mass: 21 $M_\odot$
Works where ζ Per referred to as prototype: Morgan & Keenan (1973)
Works relating ζ Per to type: Zorec et al. (2009)
General works about ζ Per: Remie & Lamers (1982); Morel et al. (2004); Zorec et al. (2009); Lamers (1981)

Alternative prototype(s): Rigel: Very well-studied – too similar to Deneb

White (BA) supergiant: Deneb [194]

Deneb *is sidereal source*
Deneb also known as: α Cyg
Reason for selection of Deneb: MK73, G94: A2 Ia standard; very well-studied; explicit prototype of variable star class
Notes on Deneb: Initial mass: 23 ± 2 $M_\odot$; mass: 18 ± 2 $M_\odot$
Works where Deneb referred to as prototype: Morgan & Keenan (1973); Garrison (1994)
General works about Deneb: Gautschy (2009); Richardson et al. (2011); Aufdenberg et al. (2002); Schiller & Przybilla (2008)

Alternative prototype(s): Rigel: Very well-studied – not prototype of α Cygni variables

Red supergiant: Betelgeuse [195]

Betelgeuse *is sidereal source*
Betelgeuse also known as: α Ori
Reason for selection of Betelgeuse: MK73: M1-M2 Ia-Ib standard; G94: M2/M2+ Ia/Ib anchor point; very well-studied
Notes on Betelgeuse: Initial mass: 20^{+5}_{-3} $M_\odot$; current mass: 19.4–19.7 $M_\odot$; variable; has circumstellar envelope
Works where Betelgeuse referred to as prototype: Morgan & Keenan (1973); Garrison (1994)
General works about Betelgeuse: Harper et al. (2008); Dolan et al. (2016); Gilliland & Dupree (1996)

Yellow hypergiant: ρ Cas [196]

Type description: Transitional stage between blue supergiant and red supergiant, frequently interpreted as post-red supergiant; occasional outbursts with mass loss episodes
Type references: Gordon & Humphreys (2019)

ρ **Cas** *is sidereal source*
Reason for selection of ρ Cas: Explicit prototype; well-studied
Works where ρ Cas referred to as prototype: Chesneau et al. (2014)
Works relating ρ Cas to type: Lobel et al. (2003); Kraus et al. (2019)
General works about ρ Cas: Lobel et al. (2003); Kraus et al. (2019)

Cool hypergiant: VY CMa [197]

Type description: Extremely bright late-type star, more extreme than red supergiants; could be either analog to red supergiants for stars with initial mass 30–40 $M_\odot$, or end of red supergiant phase
Type references: Schuster et al. (2006); Dorda et al. (2019)

VY CMa *is sidereal source*
Reason for selection of VY CMa: Explicit prototype; most cited of cool hypergiants of Schuster et al. (2006)
Notes on VY CMa: Initial mass: 25 ± 10 $M_\odot$; current mass: 17 ± 8 $M_\odot$
Works where VY CMa referred to as prototype: Montez et al. (2015)
Works relating VY CMa to type: Zhang et al. (2012a)
General works about VY CMa: Zhang et al. (2012a); Wittkowski et al. (2012); Montez et al. (2015)

1.4.6.5.3 Wolf-Rayet stars

Formed from massive or very massive stars (initial mass $\gtrsim 30$ $M_\odot$ that have suffered severe mass loss. Wolf-Rayet (WR) stars are deficient in hydrogen because the envelopes have been lost, leaving only a helium core. They are among the hottest known stars.

General references: Abbott & Conti (1987); van der Hucht (2001); Crowther (2007)

WR N: EZ CMa [198]

Type description: Have helium and nitrogen emission lines
Type references: Hamann et al. (2019)

EZ CMa *is sidereal source*
EZ CMa also known as: HD 50896; WR 6
Reason for selection of EZ CMa: Explicit prototype; most cited WR N of van der Hucht (2001) that is not X-ray binary
Notes on EZ CMa: Current mass: 23 $M_\odot$
Works where EZ CMa referred to as prototype: Morris et al. (2004)
Works relating EZ CMa to type: Morris et al. (2004); Hamann et al. (2019)
Relationships between EZ CMa and other Exotica Catalog objects: Within the sky region occupied by: S 308 [371]

WR C: γ_2 Vel [199]

Type description: Have helium, carbon, and oxygen emission lines; oxygen lines relatively weak

γ_2 **Vel** *is sidereal source*
γ_2 *Vel also known as:* WR 11
Reason for selection of γ_2 *Vel:* Most cited WR C of van der Hucht (2001) catalog; closest WR star
Notes on γ_2 *Vel:* Current mass: 9 $M_\odot$; less evolved O companion had initial mass ~ 34 $M_\odot$ so initial mass of WR star likely bigger
General works about γ_2 *Vel:* North et al. (2007)

WR O: WR 102 [200]

Type description: Have helium, carbon, and oxygen emission lines; oxygen lines relatively strong
Type references: Tramper et al. (2015)

WR 102 *is sidereal source*
Reason for selection of WR 102: Second most cited in Tramper et al. (2015); superlative temperature, elsewhere in catalog
Notes on WR 102: Current mass: 9.8 $M_\odot$
Works relating WR 102 to type: Tramper et al. (2015)
General works about WR 102: Tramper et al. (2015)

1.4.6.6 Very massive stars

Stars with initial masses above ~ 40 $M_\odot$. These stars have the full sequence of nuclear burning, but they are prevented from becoming red supergiants, likely due to mass loss (Humphreys & Davidson 1979; Woosley et al. 2002). They become 1.) blue supergiants and blue hypergiants, and then 2.) luminous blue variables and Wolf-Rayet stars

(Clark et al. 2012). The end of their lives can be marked by a CCSN, failed SN, pulsational pair instability supernova, or pair instability supernova; the final remnant is a black hole or nothing at all.

1.4.6.6.1 Blue hypergiants

B hypergiant: ζ_1 Sco [201]

Type description: Extremely bright blue star; possibly will evolve into LBVs
Type references: Clark et al. (2012)

ζ_1 **Sco** *is sidereal source*
Reason for selection of ζ_1 *Sco:* Well-studied; not LBV, X-ray binary, or extremely obscured
Notes on ζ_1 *Sco:* B1.5 Ia+
Works relating ζ_1 *Sco to type:* Clark et al. (2012)

1.4.6.6.2 Luminous Blue Variables

Unstable blue hypergiants with strong variability.

Abbreviation for general class: LBVs
General references: Humphreys & Davidson (1994); Humphreys (1999); van Genderen (2001)

S Dor-type luminous blue variable: AG Car [202]

Type description: LBV lacking extreme outbursts; variability of ~ 2 magnitudes in V-band on timescales of about a decade (irregular eruptions)
Type references: van Genderen (2001); Groh et al. (2009)

AG Car *is sidereal source*
Reason for selection of AG Car: Explicit prototype
Works where AG Car referred to as prototype: Groh et al. (2009)
Works relating AG Car to type: Groh et al. (2009)

Alternative prototype(s): S Dor: eponym – distant, in LMC

η **Car-like luminous blue variable:** η Car [203]

Type also known as: Supernova impostors
Type description: LBVs with giant eruptions ($\sim$ 4–8 magnitudes in V-band) with recurrence time of decades or longer, associated with mass loss of several $M_\odot$
Notes on type: Separateness of class questioned by van Genderen (2001)
Type references: Humphreys (1999); Humphreys et al. (1999); Smith et al. (2011)

η **Car** *is sidereal source*
Reason for selection of η *Car:* Explicit prototype; most famous example; well-studied
Notes on η *Car:* In binary with less massive WR star; current masses: $\sim 100\ M_\odot$ (LBV), $\sim 30\ M_\odot$ (WR secondary)
Works where η *Car referred to as prototype:* Humphreys et al. (1999); Massey et al. (2007)
Works relating η *Car to type:* Hillier et al. (2001)
General works about η *Car:* Hillier et al. (2001); Smith & Frew (2011); Shull & Danforth (2019); Davidson & Humphreys (1997)
Relationships between η *Car and other Exotica Catalog objects:* Within the sky region occupied by: Homunculus Nebula [370]

Alternative prototype(s): P Cyg: other historically observed Milky Way example

1.4.7 Peculiar stars

A heterogeneous catch-all for a variety of stars displaying abnormal phenomena.

1.4.7.1 Chemically peculiar stars

There are a large variety of chemically peculiar stars among B and A dwarfs, including the Ap, Am, and HgMn stars. These subtypes are thought to be driven by the diffusion of different elements in stars that are slowly rotating and do not have convective surfaces.

The λ Boötis stars' peculiarities through a different (but poorly understood) mechanism involving accretion of material.

General references: Preston (1974); Vauclair & Vauclair (1982); Renson & Manfroid (2009)

Metallic-line (Am) star: ϵ Ser [204]

Type also known as: CP1 star

Type description: Early-type dwarf with strong metal lines in spectrum but lacking a strong magnetic field and with weak Ca II or Sc II lines; slowly rotating and probably tidally locked with companion, allowing elements to segregate

Type references: Abt & Levy (1985)

ϵ **Ser** *is sidereal source*

Reason for selection of ϵ Ser: Highly cited among those of Abt & Levy (1985); measured magnetic field is relatively weak; A-type standard star in Allende Prieto & del Burgo (2016); in I17

Notes on ϵ Ser: Magnetic field strength: 9.2–70.7 G (Bychkov et al. 2009)

Works relating ϵ Ser to type: Abt & Levy (1985); Bychkov et al. (2009)

General works about ϵ Ser: Bychkov et al. (2009); Abt & Levy (1985); Allende Prieto & del Burgo (2016)

ϵ Ser in I17

Magnetic Ap star: α_2 CVn [205]

Type also known as: Magnetic chemically peculiar (mCP) star; CP2 star

Type description: Early-type dwarf with detectable magnetic field, not result of dynamo but apparently remnant field; also chemically peculiarities in patches, including overabundances of elements like silicon, strontium, and chromium

Type references: Kochukhov & Bagnulo (2006); Aurière et al. (2007); Silvester et al. (2012)

α_2 **CVn** *is sidereal source*

α_2 CVn also known as: Cor Caroli

Reason for selection of α_2 CVn: Explicit prototype; most cited of Babcock (1958) and Silvester et al. (2012); in I17

Works where α_2 CVn referred to as prototype: Kochukhov & Wade (2010)

Works relating α_2 CVn to type: Kochukhov & Wade (2010)

α_2 CVn in I17

Mercury-manganese star: α And A [206]

Type also known as: HgMn star; CP3 star

Type description: Early-type dwarf with strong Hg II and Mn II absorption lines, and overabundances of some other elements; weak magnetic fields; generally hotter than Am stars

Type references: Wolff & Preston (1978); Makaganiuk et al. (2011)

α **And A** *is sidereal source*

α And A also known as: Alpheratz A

Reason for selection of α And A: Brightest example; most cited of Wolff & Preston (1978); in I17

Caveats about selection of α And A: Displays unusual variability in Hg II λ3984 line

Notes on α And A: In binary system

Works relating α And A to type: Wade et al. (2006)

General works about α And A: Branham (2017); Wade et al. (2006)

α And A in I17

λ **Boötis star:** λ Boo [207]

Type description: Star with depletions in iron-peak elements relative to other elements, presumably due to accretion of material deficient in dust

Type references: Venn & Lambert (1990); Murphy & Paunzen (2017)

λ **Boo** *is sidereal source*

Reason for selection of λ Boo: Eponym; in I17

General works about λ Boo: Murphy & Paunzen (2017); Gerbaldi et al. (2003); Ciardi et al. (2007); Venn & Lambert (1990)
λ Boo in I17

1.4.8 Population II stars

Stars with low metallicity, formed in early epochs of galactic chemical evolution. In the Milky Way, Population II stars are found in the halo, thick disk, and bulge. Stars with Solar-like metallicity are Population I stars and have been covered with the above prototypes. Population II stellar evolution is basically the same as Population I evolution, but the stars are displaced on the HR diagram.

The spectral type is prefixed with "sd", standing for "subdwarf". These are cool subdwarfs, and have no relation to hot subdwarfs resulting from stellar interactions.

1.4.8.1 Population II brown dwarf

sdL: 2MASS J0532+8246 [208]

2MASS J0532+8246 *is sidereal source*
Reason for selection of 2MASS J0532+8246: One of first discovered; first with parallax; one of coolest known
Works relating 2MASS J0532+8246 to type: Burgasser et al. (2008)
General works about 2MASS J0532+8246: Burgasser et al. (2008)

1.4.8.2 Population II dwarfs

The Population II main sequence appears to fall below the Population I main sequence. Only low mass Population II dwarfs, with late spectral types, survive.

General class also known as: Cool subdwarfs

sdM: Kapteyn's star [209]

Kapteyn's star *is sidereal source*
Kapteyn's star also known as: GJ 191
Reason for selection of Kapteyn's star: Nearest halo star; one of nearest stars; in I17
Notes on Kapteyn's star: Spectral classification: dM2; [Fe/H]: -0.96; planets claimed (Anglada-Escude et al. 2014) but disputed (Robertson et al. 2015)
Works relating Kapteyn's star to type: Jao et al. (2008)
General works about Kapteyn's star: Robertson et al. (2015); Anglada-Escude et al. (2014)
Kapteyn's star in I17

sdK: Groombridge 1830 [210]

Groombridge 1830 *is sidereal source*
Groombridge 1830 also known as: GJ 451; HD 103095
Reason for selection of Groombridge 1830: H15 benchmark; nearby star
Caveats about selection of Groombridge 1830: H15: spectral type G8
Notes on Groombridge 1830: [Fe/H]: -1.50
Works relating Groombridge 1830 to type: Creevey et al. (2012); Karovicova et al. (2018)
General works about Groombridge 1830: Karovicova et al. (2018); Creevey et al. (2012); Heiter et al. (2015)

sdG: BD -00 4470 [211]

BD -00 4470 *is sidereal source*
Reason for selection of BD -00 4470: Fifth most cited star and only sdG in Gizis (1997), and fifth-most cited star
Notes on BD -00 4470: [Fe/H]: -1.76
Works relating BD -00 4470 to type: Mortier et al. (2012)

sdF: HD 84937 [212]

HD 84937 *is sidereal source*

Reason for selection of HD 84937: H15 benchmark
Notes on HD 84937: H15: spectral type sdF5, [Fe/H] = -2.03
Works where HD 84937 referred to as prototype: Heiter et al. (2015)
Works relating HD 84937 to type: Sneden et al. (2016)
General works about HD 84937: Heiter et al. (2015)

1.4.8.3 Population II post-main sequence

Population II subgiant: HD 140283 [213]

HD 140283 *is sidereal source*
Reason for selection of HD 140283: H15 benchmark; one of nearest halo stars
Works where HD 140283 referred to as prototype: Heiter et al. (2015)
Works relating HD 140283 to type: Bond et al. (2013)
General works about HD 140283: Creevey et al. (2015); Bond et al. (2013); Heiter et al. (2015)

1.4.8.4 Extremely metal poor stars

Stars with much lower metallacity than typical Population II star, with [Fe/H] $\ll -2$.

Extremely metal poor star: HD 122563 [214]

Type references: Norris et al. (2013)

HD 122563 *is sidereal source*
Reason for selection of HD 122563: H15 benchmark; highly cited (fourth-most in Beers et al. 1985; second-most in Ryan et al. 1996
Notes on HD 122563: [Fe/H]: -2.64; red giant
General works about HD 122563: Heiter et al. (2015)

Carbon enhanced metal poor (intrinsic) star: HE 0107-5240 [215]

Type also known as: CEMP
Type description: Very low iron abundance, but carbon abundance is not unusually low; high [C/Fe] is not due to pollution by companion star, but presumably inherent in gas that formed star
Type references: Aoki et al. (2007); Masseron et al. (2010); Norris et al. (2013)

HE 0107-5240 *is sidereal source*
Reason for selection of HE 0107-5240: First known
Caveats about selection of HE 0107-5240: Intrinsic status not certain
Notes on HE 0107-5240: [Fe/H] = -5.54, [C/Fe] = +3.85; red giant
Works relating HE 0107-5240 to type: Christlieb et al. (2002); Masseron et al. (2010); Norris et al. (2013)

1.4.9 Pulsational variable star

General references: Gautschy & Saio (1995, 1996); Pietrukowicz et al. (2017)

1.4.9.1 Pulsating giants and supergiants

Long-period variable: Mira A [216]

Type description: AGB star showing long-period variability; dusty envelopes

Mira A *is sidereal source*
Mira A also known as: o Cet
Reason for selection of Mira A: Explicit prototype and eponym; highly cited
Notes on Mira A: Also weakly symbiotic binary with white dwarf companion
Works where Mira A referred to as prototype: Sokoloski & Bildsten (2010); Wong et al. (2016)
General works about Mira A: Sokoloski & Bildsten (2010); Chandler et al. (2007); Vlemmings et al. (2015); Ramstedt et al. (2014); Wong et al. (2016)

α Cygni variable: Deneb [194]

Type description: Pulsating early-type supergiant; not related to iron-opacity driven variables or luminous blue variables
Type references: van Genderen (1989); Gautschy (2009)

Deneb *is sidereal source*
Deneb also known as: α Cyg
Reason for selection of Deneb: Eponym and explicit prototype; elsewhere in catalog
Works where Deneb referred to as prototype: Gautschy (2009); Richardson et al. (2011)
Works relating Deneb to type: Gautschy (2009); Richardson et al. (2011)
General works about Deneb: Gautschy (2009); Morgan & Keenan (1973); Richardson et al. (2011); Aufdenberg et al. (2002); Schiller & Przybilla (2008); Garrison (1994)

Alternative prototype(s): Rigel: Very well-studied – not prototype of α Cygni variables

1.4.9.2 Helium instability strip variables

Variable stars in the classical instability strip in the HR diagram. Their variability is the result of the κ (opacity) mechanism applied to helium opacity.

Cepheid: δ Cep [187]

Type description: Pulsating supergiant in the instability strip; large magnitude variations
Notes on type: Discrepant masses between evolutionary models and pulsations characteristic of Cepheids (Cox 1980)
Type references: Leavitt & Pickering (1912); Cox (1980); Fernie (1990); Madore & Freedman (1991); Monson et al. (2012)

δ **Cep** *is sidereal source*
Reason for selection of δ Cep: Eponym; highly cited; elsewhere in catalog
Notes on δ Cep: Initial mass: 5.5 $M_\odot$; mass measured with pulsations: 4.5 $M_\odot$
Works relating δ Cep to type: Natale et al. (2008)
General works about δ Cep: Natale et al. (2008); Matthews et al. (2012)

Relationship to SETI: Learned et al. (2008) proposes ETI beacons via the modulation of Cepheid variability using neutrino beams to heat stellar interiors

RR Lyrae variable: RR Lyr [172]

Type description: Pulsating giant star in instability strip
Notes on type: Strictly speaking, only refers to Population I giants in instability strip
Type references: Benedict et al. (2011)

RR Lyr *is sidereal source*
Reason for selection of RR Lyr: Eponym; highly cited; elsewhere in catalog
General works about RR Lyr: Benedict et al. (2011)

δ Scuti variable: δ Sct [217]

Type description: Pulsating main sequence star in instability strip; small fluctuations typically up to ~ 0.2 mag
Type references: Rodríguez et al. (2000)

δ **Sct** *is sidereal source*
Reason for selection of δ Sct: Eponym; second most cited in Rodríguez et al. (2000) after β Cas; relatively high variability (0.19 mag)
Works relating δ Sct to type: Rodríguez et al. (2000)

1.4.9.3 γ Dor variables

γ Doradus variable: γ Dor [218]

Type description: Non-radial pulsating A or F dwarf; oscillations are g-modes, thought to be driven at base of convection

zone
Type references: Kaye et al. (1999); Guzik et al. (2000); Uytterhoeven et al. (2011)

γ **Dor** *is sidereal source*
Reason for selection of γ Dor: Eponym and explicit prototype
Works where γ Dor referred to as prototype: Kaye et al. (1999)
Works relating γ Dor to type: Balona et al. (1994); Kaye et al. (1999)
γ Dor in I17

1.4.9.4 Early-type pulsators

Variable stars of spectral type O and B. Most are driven by the κ mechanism applied to iron opacity, resulting in a parallel instability strip.

Slowly Pulsating B variable: 53 Per [219]

Abbreviations for type: SPB
Type description: Pulsating B dwarfs and giants; oscillations are g-modes driven by iron opacity; generally cooler and lower mass than β Cep stars
Type references: Waelkens (1991); Degroote et al. (2009)

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53 Per *is sidereal source*
Reason for selection of 53 Per: Early discovery; eponym of the 53 Per variables which encompass SPB
Works relating 53 Per to type: Waelkens (1991); Chapellier et al. (1998); De Ridder et al. (1999)

β **Cep variable:** β Cep [220]

Type also known as: β CMa variable
Type description: Pulsating B dwarfs and giants; oscillations are p-modes driven by iron opacity; generally hotter and more massive than 53 Per stars
Type references: Stankov & Handler (2005); Degroote et al. (2009)

β **Cep** *is sidereal source*
β Cep also known as: Alfirk
Reason for selection of β Cep: Eponym of β Cep variables; third most cited of Stankov & Handler (2005) after σ Sco and Spica
Notes on β Cep: Actually part of a triple system. As the primary of the inner larger binary, it could be called β Cep Aa, but in practice, this star is usually referred to as simply β Cep (e.g., Nardetto et al. 2011; Henrichs et al. 2013). (Note that Catanzaro (2008) refers to the secondary of the inner primary as β Cep Aa instead of β Cep Ab.) The companions are a nearby Be star (Ab), 3.4 mag fainter (Schnerr et al. 2006), and a still fainter star further out.
General works about β Cep: Henrichs et al. (2013); Nardetto et al. (2011); Gordon et al. (2019); Catanzaro (2008); Schnerr et al. (2006)

Blue large amplitude pulsator: OGLE BLAP-009 [221]

Abbreviations for type: BLAP
Type description: Blue stars between classical hot subdwarfs and main sequence with ~ 0.3 mag oscillations driven by iron opacity
Notes on type: Evolutionary status disputed: have been claimed to be subdwarfs, pre-white dwarfs (Romero et al. 2018), core helium burning stars (Wu & Li 2018), and surviving donors of Type Ia supernovae (Meng et al. 2020)
Type references: Pietrukowicz et al. (2017)

OGLE BLAP-009 *is sidereal source*
Reason for selection of OGLE BLAP-009: Nearest and brightest; spectroscopically studied
Works relating OGLE BLAP-009 to type: Pietrukowicz et al. (2017)

Alternative prototype(s): OGLE-BLAP-001: explicit prototype and first discovered – further, less well studied

Slowly pulsating sdBV: PG 1716+426 [222]

Type description: B subdwarf with ~ 0.01 mag g-mode pulsations driven by iron opacity; periods of hours
Type references: Green et al. (2003); Fontaine et al. (2003)

PG 1716+426 *is sidereal source*
Reason for selection of PG 1716+426: Explicit prototype
Works where PG 1716+426 referred to as prototype: Green et al. (2003); Kilkenny et al. (2010)

Rapidly-pulsating sdBV: V361 Hya [223]

Type description: B subdwarf with ~ 0.01 mag p-mode pulsations driven by iron opacity; periods of minutes
Type references: Green et al. (2003); Fontaine et al. (2003)

V361 Hya *is sidereal source*
V361 Hya also known as: EC 14026-2647
Reason for selection of V361 Hya: Explicit prototype
Works where V361 Hya referred to as prototype: Kilkenny et al. (1997, 2010)

Pulsating sdO: SDSS J160043.6+074802.9 [224]

Type description: Pulsating O subdwarf, probably not driven by iron opacity
Notes on type: There may be several subtypes of these, including the "blue hook" stars, cooler sdOVs found in ω Cen, which could be helium sdO (Latour et al. 2018)
Type references: Fontaine et al. (2008); Randall et al. (2011, 2016)

SDSS J160043.6+074802.9 *is sidereal source*
Reason for selection of SDSS J160043.6+074802.9: First discovered; explicit prototype
Works where SDSS J160043.6+074802.9 referred to as prototype: Kilkenny et al. (2010)
Works relating SDSS J160043.6+074802.9 to type: Woudt et al. (2006)
General works about SDSS J160043.6+074802.9: Latour et al. (2011)

1.4.10 Active stars

1.4.10.1 Flare stars

General references: Schaefer (1989); Haisch et al. (1991)

dMe: UV Cet [225]

Type description: M dwarf with powerful stellar flares resultant from magnetic activity
Type references: Hilton et al. (2010); Kowalski et al. (2013); Yang et al. (2017b)

UV Cet *is sidereal source*
UV Cet also known as: GJ 65B
Reason for selection of UV Cet: Explicit prototype; nearby; in I17
Notes on UV Cet: Companion to BL Cet
Works where UV Cet referred to as prototype: Haisch et al. (1991)
Works relating UV Cet to type: Eason et al. (1992)
General works about UV Cet: Kervella et al. (2016a); Benedict et al. (2016)
UV Cet in I17
Relationships between UV Cet and objects in I17: Is mutually orbiting: GJ 65A

Alternative prototype(s): Proxima Cen: nearest star besides Sun, well-studied, elsewhere in catalog and I17
Relationship to SETI: Flares may help chemical synthesis of biomolecules (Buccino et al. 2007; Ranjan et al. 2017) or limit the habitability of planets in the habitable zones of red dwarfs (Yamashiki et al. 2019; c.f. Segura et al. 2010)

Superflare star: κ_1 Cet [149]

Type description: Star (including G dwarfs) that emits flares of energy $\gtrsim 10^{33}$ erg (up to 10^{38} erg), about ten times greater than observed so far on the Sun
Notes on type: Although it was once thought that hot Jupiters were a necessary prerequisite for superflares (Rubenstein &

Schaefer 2000), this has not been borne out by *Kepler* statistics (e.g., Candelaresi et al. 2014). The superflare rate and energy may be limited by the magnetic energy associated with starspots (e.g., Shibayama et al. 2013; Notsu et al. 2019). It is possible that all solar-type stars – including the Sun – are superflare stars, if at low rates or energies.

Type references: Schaefer et al. (2000); Maehara et al. (2012); Shibata et al. (2013); Shibayama et al. (2013); Candelaresi et al. (2014); Notsu et al. (2019)

κ_1 **Cet** *is sidereal source*

Reason for selection of κ_1 *Cet:* Most cited star of Schaefer et al. (2000) sample; nearby; elsewhere in catalog; in I17

Notes on κ_1 *Cet:* Single superflare of energy 2×10^{34} erg observed in 1986 (Robinson & Bopp 1987); Lynch et al. (2019) speculates that this is a nearly maximal flare for κ_1 Ceti; stellar age: $\sim 0.6 \pm 0.2$ Gyr (Ribas et al. 2010)

Works relating κ_1 *Cet to type:* Lynch et al. (2019)

General works about κ_1 *Cet:* do Nascimento et al. (2016); Garrison (1994); Ribas et al. (2010)

κ_1 *Cet in I17*

Relationship to SETI: Superflares may damage planetary ecosystems; a superflare on the Sun would catastrophically damage electrical systems on Earth (Lingam & Loeb 2017a)

RS CVn-type flare star: HR 1099 [226]

Type description: Component star of active binary that emits large (up to 10^{39} erg s^{-1}) multiwavelength (super)flares, due to enhanced activity in binary system

Relationship with other types: Phenomenon occurs in detached active binary stars

Type references: Osten & Brown (1999); Sanz-Forcada et al. (2002)

HR 1099 *is sidereal source*

HR 1099 also known as: V711 Tau; HD 22468

Reason for selection of HR 1099: Early discovery; well-studied; in I17

Notes on HR 1099: System contains K1 IV primary with a G5 V companion (Osten et al. 2004)

Works relating HR 1099 to type: White et al. (1978); Linsky et al. (1989)

General works about HR 1099: Osten et al. (2004)

HR 1099 in I17

1.4.10.2 Stellar pulsars

Stars that display periodic bursts of coherent radio emission as they rotate.

Ultracool pulsar: TVLM 513-46546 [227]

Type description: Ultracool dwarf that pulsates in radio; cyclotron maser mechanism involving stellar magnetic fields; radio pulses are broadband and circularly polarized; also optical periodic variability

Type references: Hallinan et al. (2008); Harding et al. (2013)

TVLM 513-46546 *is sidereal source*

Reason for selection of TVLM 513-46546: Explicit prototype; one of first recognized

Works where TVLM 513-46546 referred to as prototype: Harding et al. (2013)

Works relating TVLM 513-46546 to type: Hallinan et al. (2007)

mCP pulsar: CU Vir [228]

Type description: Magnetic chemically peculiar (Ap/Bp) star with periodic radio and optical emission; radio emission is polarized; mechanism presumably cyclotron maser emission

Type references: Das et al. (2019a)

CU Vir *is sidereal source*

Reason for selection of CU Vir: First example recognized

Notes on CU Vir: Rotation period accelerates and decelerates over decades; mechanisms require stellar wind but none yet detected; frequently described as puzzling in literature

Works relating CU Vir to type: Kellett et al. (2007); Trigilio et al. (2008); Ravi et al. (2010)

General works about CU Vir: Krtička et al. (2019); Mikulášek et al. (2011)

1.4.11 Rotationally extreme stars

Classical Be stars: ζ Tau [229]

Type description: B star spinning near break-up speed; has decretion disk spun off star; spectrum has emission lines
Notes on type: Shell Be stars are classical Be systems viewed edge on
Type references: Porter & Rivinius (2003); Rivinius et al. (2013)

ζ **Tau** *is sidereal source*
Reason for selection of ζ Tau: Well-studied; fifth most cited Be within 300 pc on Simbad, one of most-cited that is typical of class
Notes on ζ Tau: Shell Be star
Works relating ζ Tau to type: Schaefer et al. (2010); Kraus et al. (2012); Escolano et al. (2015)

1.4.12 Post merger-interaction stars

Stars that are the result of non-standard evolution caused by mass transfer in a close binary. In extreme cases, they can be the aftermath of stellar mergers, or white dwarf mergers, after a common envelope phase (Paczynski 1976). The resulting objects are heterogeneous.

1.4.12.1 Stellar merger products

Luminous red nova: V838 Mon [230]

Type description: Transients with luminosities between novae and supernovae, resulting from merger of contact binaries; includes here the very early post-merger stages
Type references: Mould et al. (1990); Tylenda et al. (2011)

V838 Mon *is sidereal source*
Reason for selection of V838 Mon: Prominent example, one of best studied
Notes on V838 Mon: Briefly was brightest star in Galaxy
Works relating V838 Mon to type: Munari et al. (2002); Kimeswenger et al. (2002); Bond et al. (2003)
General works about V838 Mon: Evans et al. (2003); Munari et al. (2002); Sparks et al. (2008)

Alternative prototype(s): V1309 Sco: contact binary progenitor confirmed

Yellow straggler: M67-S1237 [231]

Type description: Later stage of evolution of blue straggler, abnormally high mass star for stellar population due to stellar merger

M67-S1237 *is sidereal source*
Reason for selection of M67-S1237: Example with known mass, evolutionary state
Works relating M67-S1237 to type: Leiner et al. (2016)
Relationships between M67-S1237 and other Exotica Catalog objects: Within the sky region occupied by: M67 [335]; Adjacent on sky to (sharing parent object with): M67-S1063 [685]

FK Comae star: FK Com [232]

Type description: Yellow giants with extremely rapid rotation, result of stellar merger
Type references: Bopp & Stencel (1981)

FK Com *is sidereal source*
Reason for selection of FK Com: Eponym; well-studied
General works about FK Com: Ayres et al. (2016)

R CrB star: R CrB [233]

Type description: F or G supergiant with extreme fading episodes of several magnitudes due to dust cloud condensation in stellar atmosphere; probably product of white dwarf-white dwarf merger; very rare

Caveats about type: Some R CrB stars may be post-AGB stars (Clayton et al. 2011)
Type references: Webbink (1984); Clayton (1996); Lauer et al. (2019)

R CrB *is sidereal source*
Reason for selection of R CrB: Explicit prototype and eponym
Works relating R CrB to type: Jeffery (2008a); García-Hernández et al. (2011)
General works about R CrB: García-Hernández et al. (2011); Howell et al. (2013)

Extreme helium star: HD 124448 [234]

Type description: B supergiant lacking hydrogen; possibly descendant of R CrB star; probably product of white dwarf-white dwarf merger; extremely rare
Type references: Jeffery (2008b); Lauer et al. (2019)

HD 124448 *is sidereal source*
Reason for selection of HD 124448: Explicit prototype; well-studied
Works where HD 124448 referred to as prototype: Jeffery (2008a)

Blue straggler: 40 Cnc [235]

Type description: Blue main sequence star, but too old for high mass (as inferred in coveal populations, for example); result of stellar mergers
Type references: Bailyn (1995)

40 Cnc *is sidereal source*
40 Cnc also known as: HD 73666
Reason for selection of 40 Cnc: Most cited blue straggler within 1 kpc in Simbad
Notes on 40 Cnc: Member of M44
Works relating 40 Cnc to type: Fossati et al. (2010)

Relationship to SETI: Blue stragglers proposed to be artificial in Beech (1990)

1.4.12.2 Hot subdwarfs

Helium-burning stars formed by stellar mass transfer in a close binary. They have lost most of their envelopes, leaving only a thin hydrogen shell atop a helium star. They are hot and appear to sit below main sequence. In star clusters, appear to form extreme horizontal branch.

Not related to cool subdwarfs.

General references: Heber (2016)

sdB hot subdwarf: HD 149382 [236]

Type description: B-type subdwarf with hydrogen dominated atmosphere

HD 149382 *is sidereal source*
Reason for selection of HD 149382: Brightest on sky; well-cited
Works relating HD 149382 to type: Geier et al. (2017)
General works about HD 149382: Geier et al. (2009); Norris et al. (2011); Jacobs et al. (2011)

sdO hot subdwarf: BD+28 4211 [237]

Type description: O-type subdwarf with hydrogen dominated atmosphere

BD+28 4211 *is sidereal source*
Reason for selection of BD+28 4211: Most well-cited in Simbad
Works relating BD+28 4211 to type: Geier et al. (2017)

Helium subdwarf: PG 1544+488 [238]

Abbreviations for type: He-sdOB
Type description: Hot (O or B) subdwarf with atmosphere dominated by helium

PG 1544+488 *is sidereal source*

Reason for selection of PG 1544+488: Explicit prototype
Notes on PG 1544+488: Actually is a binary of nearly identical helium sdB stars, an unusual occurence
Works where PG 1544+488 referred to as prototype: Ahmad et al. (2004, 2007); Jeffery (2008a)
Works relating PG 1544+488 to type: Ahmad et al. (2004); Şener & Jeffery (2014)

1.4.12.3 AGB-polluted stars

Stars with chemical peculiarities resulting from the capture of some of the mass loss of an AGB companion. Several subtypes exist, including CEMP-s stars, Ba stars, and CH stars.

General references: McClure et al. (1980); Smith (1992); Aoki et al. (2007); Margon et al. (2018); Whitehouse et al. (2018)

Dwarf carbon star: G77-61 [239]

G77-61 *is sidereal source*
Reason for selection of G77-61: Explicit prototype; first discovered
Notes on G77-61: Has white dwarf companion, likely remnant of AGB companion; [Fe/H]: -4.0, [C/Fe]: +2.6; also can be considered a CEMP-s star
Works where G77-61 referred to as prototype: Margon et al. (2018); Whitehouse et al. (2018); Green et al. (2019)
Works relating G77-61 to type: Dearborn et al. (1986); Plez & Cohen (2005)

1.4.13 High velocity stars

Stars distinguished kinematically by having abnormally high velocity with respect to the surrounding stellar population. These high velocities are the result of gravitational interaction with another body.

Runaway star: ζ Oph [240]

Type description: High velocity (typically $\sim$ 30 km s^{-1}; $\lesssim$ 500 km s^{-1}) early-type star; could be former companion of star that went supernova, became unbound; alternatively, could be ejected from cluster during stellar encounter
Type references: Hoogerwerf et al. (2001); Silva & Napiwotzki (2011)

ζ **Oph** *is sidereal source*
Reason for selection of ζ Oph: Well-known; most cited of Blaauw (1961)
Notes on ζ Oph: Has bow shock nebula; velocity: 23.5 km s^{-1}, relatively low for runaway stars
Works relating ζ Oph to type: Hoogerwerf et al. (2000); del Valle & Romero (2012); Gvaramadze et al. (2012)
General works about ζ Oph: Gordon et al. (2018)
Relationships between ζ Oph and other Exotica Catalog objects: Within the sky region occupied by: ζ Oph cloud [349], ζ Oph bow shock [363]

Hyperrunaway star: HD 271791 [241]

Type description: Extreme velocity star or white dwarf ($\sim$ 500–1,500 km s^{-1}, unbound from Galaxy) thought to be ejected by supernova; Type Ia supernova with compact stars/remnants needed to achieve highest speeds; progenitors may originate from anywhere in galaxy
Type references: Geier et al. (2015); Shen et al. (2018)

HD 271791 *is sidereal source*
Reason for selection of HD 271791: Known to come from outer Galaxy
Notes on HD 271791: Galactic rest-frame velocity: 500–900 km s^{-1}
Works relating HD 271791 to type: Heber et al. (2008); Przybilla et al. (2008)

Hypervelocity stars: HVS 1 [242]

Type description: Extreme velocity star thought to be ejected from center of galaxy by dynamical interaction with central black hole; might also originate by tidal disruption of dwarf galaxy in halo
Type references: Abadi et al. (2009); Brown (2015)

HVS 1 *is sidereal source*

Reason for selection of HVS 1: First known
Works relating HVS 1 to type: Brown et al. (2005b)

1.5 Collapsed stars

A phylum that includes the three main types of stellar remnants: white dwarfs, neutron stars, and stellar-mass black holes. They are either totally collapsed (black holes), or usually being supported by degeneracy pressure (white dwarfs and neutron stars). Nuclear fusion is a subdominant source of internal luminosity, although it can still be significant in white dwarfs. Instead, the internal luminosity is dominated by the release of stored thermal, rotational, or magnetic energy.

Arguably, this phylum should be split into three, because the three different subcategories are so different (and ETIs would need very different methods to exploit them). As with the Stars phylum, there are a few edge cases. White dwarfs as a whole could arguably be placed under the Stars phylum. Some white dwarfs that have been "inflated" into subdwarfs after interaction with a companion are included here, while suspected larger white dwarf merger products are included in "stars". Accreting binary systems include Collapsed stars, but the system as a whole is (also) counted under Interacting binary stars.

1.5.1 White dwarfs

Our primary way of classifying white dwarfs is by their mass and, relatedly, composition, because these indicate the different formation channels and different binary evolution. Spectral types, which are tied to atmospheric conditions are also included (Sion et al. 1983). There are supplemental subtypes based on evolutionary, magnetic, or variability characteristics.

Abbreviation for general class: WD

1.5.1.1 Mass classification

Extremely Low Mass white dwarf: NLTT 11748 [243]

Abbreviations for type: ELM white dwarf; ELM WD
Type description: Mass < 0.3 $M_\odot$; helium composition; formed when progenitor envelope stripped by close stellar companion, leaving only small core.
Type references: Nelemans et al. (2001); Brown et al. (2016)

NLTT 11748 *is sidereal source*
Reason for selection of NLTT 11748: In eclipsing WD-WD binary with determined properties; relatively well studied: most cited ELM WD in Brown et al. (2016)
Works relating NLTT 11748 to type: Kawka et al. (2010); Kilic et al. (2010a)
General works about NLTT 11748: Kawka et al. (2010); Steinfadt et al. (2010); Kaplan et al. (2014a); Kawka & Vennes (2009); Kilic et al. (2010a)

Low mass white dwarfs: LAWD 32 [244]

Type description: Mass of 0.3–0.5 $M_\odot$; may form through extreme stellar wind mass loss, but usually through common envelope binary evolution; small peak in local WD mass distribution at 0.4 $M_\odot$
Type references: Liebert et al. (2005); Kilic et al. (2007b); Rebassa-Mansergas et al. (2011); Brown et al. (2011)

LAWD 32 *is sidereal source*
LAWD 32 also known as: PG 0943+441; G 116-52
Reason for selection of LAWD 32: Most cited low-mass WD of Kilic et al. (2010c)
Caveats about selection of LAWD 32: Mass measured by Bédard et al. (2017): 0.46 ± 0.11 $M_\odot$, could actually be too big to qualify – Gianninas et al. (2011) estimate mass of 0.45 ± 0.02 $M_\odot$

Typical mass white dwarf: van Maanen 2 [245]

Type description: Mass of 0.5–0.7 $M_\odot$, typically 0.6 $M_\odot$; remnant of low-mass star; carbon-oxygen composition
Type references: Liebert et al. (2005)

van Maanen 2 *is sidereal source*
Reason for selection of van Maanen 2: Nearest single white dwarf to Sun
Notes on van Maanen 2: Mass: ~ 0.67 $M_\odot$; effective temperature: $\sim$ 6,100 K
General works about van Maanen 2: Subasavage et al. (2017); Holberg et al. (2016)

Massive white dwarf: Sirius B [246]

Type description: Mass of $\sim$ 0.8–1.1 $M_\odot$; remnant of intermediate-mass star; typically carbon-oxygen composition
Type references: Liebert et al. (2005); Kleinman et al. (2013)

Sirius B *is sidereal source*
Reason for selection of Sirius B: Famous example of WD; nearest WD
Notes on Sirius B: Mass: 0.93–1.02 $M_\odot$
Works relating Sirius B to type: Joyce et al. (2018b)
General works about Sirius B: Joyce et al. (2018a); Holberg et al. (2016); Joyce et al. (2018b)
Sirius B in I17
Relationships between Sirius B and objects in I17: Is mutually orbiting: Sirius A

Ultramassive white dwarfs: GD 50 [247]

Type description: Mass $\gtrsim$ 1.1 $M_\odot$; either remnant of transition-mass star or formed through binary star channel; can be carbon-oxygen or oxygen-neon-magnesium composition
Type references: Camisassa et al. (2019)

GD 50 *is sidereal source*
Reason for selection of GD 50: Most well-cited of Vennes (1999); Camisassa et al. (2019)
Notes on GD 50: Mass: 1.25 $M_\odot$
Works relating GD 50 to type: Dobbie et al. (2006)

1.5.1.2 Evolutionary classification

Central Star of Planetary Nebula: NGC 7293 central star [077]

Abbreviations for type: CSPN
Type description: Newly exposed core of former low- or intermediate-mass star that has ejected envelopes, found in center of planetary nebula

NGC 7293 central star *is sidereal source*
Reason for selection of NGC 7293 central star: Elsewhere in catalog; host is well-known and elsewhere in catalog
General works about NGC 7293 central star: Su et al. (2007)
Relationships between NGC 7293 central star and other Exotica Catalog objects: Within the sky region occupied by: Helix Nebula [365]

Pre-white dwarf: PG 1159-035 [248]

Type description: Bare core of low- or intermediate-mass star; still transitioning to white dwarf sequence
Notes on type: Placed as collapsed star because nuclear burning has ceased and envelope has been ejected
Type references: Jahn et al. (2007)

PG 1159-035 *is sidereal source*
Reason for selection of PG 1159-035: Explicit prototype of subclass of extremely hot and hydrogen-deficient pre-WDs; well-studied
Works where PG 1159-035 referred to as prototype: Jahn et al. (2007)

1.5.1.2.1 Post-interaction white dwarfs

Partially burned inflated white dwarf: GD 492 [249]

Type description: Remnant of white dwarf that has undergone a single degenerate thermonuclear (Type Ia) supernova

due to accretion; former recipient in interacting binary; is inflated with $\log g$ more like a dwarf star due to remaining heat
Notes on type: These tend to be hyperrunaway objects but with smaller velocities than the post-double degenerate inflated white dwarfs; SDSS J1240+6710 may be an example of another subtype where progenitor had lower mass Gänsicke et al. (2020).
Type references: Vennes et al. (2017); Raddi et al. (2019); Gänsicke et al. (2020)

GD 492 *is sidereal source*
GD 492 also known as: LP 40-365
Reason for selection of GD 492: Explicit prototype; first discovered
Works where GD 492 referred to as prototype: Raddi et al. (2019)
General works about GD 492: Vennes et al. (2017); Raddi et al. (2018)

Post-double degenerate inflated white dwarf: D6-3 [250]

Type description: Remnant of donor white dwarf in double white dwarf system that has undergone a double degenerate thermonuclear (Type Ia) supernova; is inflated and resembles a hot subdwarf due to deposited heat
Notes on type: These include hyperrunaway objects with some of the highest velocities identified.
Type references: Shen et al. (2018); Raddi et al. (2019)

D6-3 *is sidereal source*
Reason for selection of D6-3: Among first identified; elsewhere in catalog
Works relating D6-3 to type: Shen et al. (2018)
General works about D6-3: Shen et al. (2018)

Alternative prototype(s): US 708: earlier discovery – classification uncertain

1.5.1.3 Classification by internal composition

Helium core white dwarf: NLTT 11748 [243]

Type description: Low mass white dwarf dominated by helium in terms of mass; atmosphere can be hydrogen or helium; result of mass transfer (or possibly severe mass loss) truncating evolution of star before it can burn helium
Notes on type: Trillions of years from now, under natural conditions, isolated red dwarfs will evolve into these making them the most numerous type of stellar remnant
Type references: Kilic et al. (2007b)

NLTT 11748 *is sidereal source*
Reason for selection of NLTT 11748: In eclipsing binary, with well-determined characteristics; most cited of Brown et al. (2016); one of the nearest ELM white dwarfs; elsewhere in catalog
Works relating NLTT 11748 to type: Steinfadt et al. (2010)
General works about NLTT 11748: Kawka et al. (2010); Steinfadt et al. (2010); Kaplan et al. (2014a); Kawka & Vennes (2009); Kilic et al. (2010a)

ONeMg white dwarf: QU Vul [251]

Type description: Remnant of transition-mass stars; internal oxygen-neon-magnesium composition although atmosphere generally contains lighter elements; start out ultramassive, but can be eroded by repeated novae; believed to be WD type involved in neon novae
Notes on type: Composition can be difficult to determine because of atmosphere

QU Vul *is sidereal source*
Reason for selection of QU Vul: Explict prototype of neon nova
Caveats about selection of QU Vul: Models exist where neon novae and QU Vul specifically are not ONeMg WDs (Shara & Prialnik 1994; Hachisu & Kato 2018)
Works where QU Vul referred to as prototype: Gehrz et al. (1995)
Works relating QU Vul to type: Gehrz et al. (1995, 2008); Hachisu & Kato (2018)
General works about QU Vul: Gehrz et al. (2008); Hachisu & Kato (2018); Gehrz et al. (1985); Hachisu & Kato (2016); Gehrz et al. (1995)

1.5.1.4 Spectroscopic classification

White dwarfs have their own spectral classes. They do not imply mass as the stellar main sequence would. Atmospheric composition (distinct from internal composition) is the major factor in the spectral class. Each main class has fine gradations that define surface temperature, but temperature does not determine the major class.

For DA and DB white dwarfs, we include some coarse temperature classifications, which roughly trace age. Some hybrid classes with characteristics intermediate between the main classes are omitted.

General references: Sion et al. (1983); Holberg et al. (2016)

Hot DA: G191-B2B [252]

Type description: White dwarf with hydrogen lines in spectrum (DA); high surface temperature (∼ 50,000 K); young (a few Myr old)

Type references: Bohlin et al. (1995)

G191-B2B *is sidereal source*

Reason for selection of G191-B2B: Explicit prototype and standard

Notes on G191-B2B: Temperature: 52,500 K, age: 1.50 Myr

Works where G191-B2B referred to as prototype: Bohlin et al. (1995); Preval et al. (2013)

Mid-temperature DA: Sirius B [246]

Type description: White dwarf with hydrogen lines in spectrum (DA); intermediate surface temperature (∼ 10,000–30,000 K) and age (hundreds of Myr; depends on mass)

Notes on type: DA white dwarfs are the most common spectral type (Holberg et al. 2008)

Sirius B *is sidereal source*

Reason for selection of Sirius B: Very well studied (most cited of Holberg et al. 2016); nearby; elsewhere in catalog

Notes on Sirius B: Temperature: 25,193 K; age: 110 Myr

General works about Sirius B: Joyce et al. (2018a,b); Holberg et al. (2016)

Sirius B in I17

Relationships between Sirius B and objects in I17: Is mutually orbiting: Sirius A

Cool DA: LHS 253 [253]

Type description: White dwarf with hydrogen lines in spectrum (DA); cool surface temperature (< 12,000 K in Bergeron 2001); generally old (hundreds of Myr – Gyr)

Notes on type: DA white dwarfs are the most common spectral type (Holberg et al. 2008)

LHS 253 *is sidereal source*

Reason for selection of LHS 253: Most cited of Bergeron (2001) catalog of cool white dwarfs; one of most well-cited nearby white dwarfs of Holberg et al. (2016)

Caveats about selection of LHS 253: Holberg et al. (2016) noted discrepant photometric and parallax distances and find an abnormally small mass

Notes on LHS 253: Temperature: 9185 K; age: 444 Myr

General works about LHS 253: Holberg et al. (2016); Hollands et al. (2018)

Hot DB: GD 358 [254]

Type description: White dwarf with helium lines in spectrum (DB); high surface temperature ($\gtrsim$ 20,000 K)

Notes on type: DB white dwarfs are the rarest spectral class of the main types (Holberg et al. 2008)

GD 358 *is sidereal source*

Reason for selection of GD 358: Explicit prototype of pulsating DB white dwarfs; most cited of Bergeron et al. (2011) catalog of DB white dwarfs

Notes on GD 358: Temperature: 23,650 K

Works where GD 358 referred to as prototype: Provencal et al. (2009)

Works relating GD 358 to type: Bischoff-Kim et al. (2019)

Intermediate temperature DB: LAWD 87 [255]

Type description: White dwarf with He I lines in spectrum but no hydrogen or metals (DB); moderate surface temperature ($\lesssim$ 20,000 K)
Notes on type: DB white dwarfs are the rarest spectral class of the main types (Holberg et al. 2008)

LAWD 87 *is sidereal source*
LAWD 87 also known as: LDS 749B
Reason for selection of LAWD 87: Third most cited of Bergeron et al. (2011) listing of DB white dwarfs; temperature typical of DB white dwarfs
Notes on LAWD 87: Temperature: 13,575 K (Bohlin & Koester 2008) (Bergeron et al. 2011 finds 14,380 K)
General works about LAWD 87: Bohlin & Koester (2008)

DC: Stein 2051B [256]

Type description: White dwarf with continuum spectrum; spectral lines weak if present at all
Notes on type: Note that C does not stand for "carbon" (see DQ)

Stein 2051B *is sidereal source*
Reason for selection of Stein 2051B: Nearest and brightest; mass well-studied after astrometric lensing event
General works about Stein 2051B: Sahu et al. (2017)

DZ: van Maanen 2 [245]

Type description: White dwarf has spectrum with metal absorption lines; helium-rich atmosphere but no helium lines

van Maanen 2 *is sidereal source*
Reason for selection of van Maanen 2: Nearest single white dwarf to Sun; elsewhere in catalog
General works about van Maanen 2: Subasavage et al. (2017); Holberg et al. (2016)

DQ: LAWD 37 [257]

Type description: White dwarf has spectrum with carbon (molecular and atomic) absorption lines; helium-rich atmosphere; relatively cool temperatures
Notes on type: Not generally related to the hot DQ white dwarfs

LAWD 37 *is sidereal source*
Reason for selection of LAWD 37: Nearby (fourth-nearest to Sun)
General works about LAWD 37: Holberg et al. (2016); McGill et al. (2018); Hollands et al. (2018)

DO: HZ 21 [258]

Type description: White dwarf with He II lines in spectrum; hot ($\gtrsim$ 50,000 K)
Notes on type: The O does not stand for "oxygen"; see Oxygen-line (Dox) white dwarfs

HZ 21 *is sidereal source*
Reason for selection of HZ 21: Most cited of Dreizler & Werner (1996) study and second nearest
Caveats about selection of HZ 21: Among coolest of Dreizler & Werner (1996) DOs with temperature 53,000 K
Works relating HZ 21 to type: Dreizler & Werner (1996)

Alternative prototype(s): PG 1034+001: third nearest in Dreizler & Werner (1996), hot PG 1159-class (pre-)white dwarf in a large but faint nearby planetary nebula

Hot DQ: WD 1150+012 [259]

Type description: Relatively warm ($\sim$ 20,000 K) white dwarf with carbon lines in spectrum; periodic variable
Notes on type: Possibly descendants of high mass stars or remnants of white dwarf mergers; possibly hydrogen- and helium-deficient?
Type references: Dufour et al. (2008); Williams et al. (2016)

WD 1150+012 *is sidereal source*

Reason for selection of WD 1150+012: Most cited and nearest of non-interacting pure DQ white dwarfs in Williams et al. (2016); in Dufour et al. (2008) sample
Works relating WD 1150+012 to type: Dufour et al. (2008)

Alternative prototype(s): SDSS 1426+5752: prototype of variable DQ white dwarfs (Williams et al. 2016)

Oxygen-line (Dox): SDSS 1102+2054 [260]

Type description: Atmosphere rich in oxygen, which dominates spectrum; atmosphere mostly helium
Notes on type: Dox is the notation used by Simbad; possibly are bare ONeMg white dwarfs
Type references: Gänsicke et al. (2010)

SDSS 1102+2054 *is sidereal source*
Reason for selection of SDSS 1102+2054: One of two known examples; higher C/O ratio than other example
Works relating SDSS 1102+2054 to type: Gänsicke et al. (2010)

Alternative prototype(s): SDSS 0922+2928: other example in Gänsicke et al. (2010) – less extreme C/O ratio

1.5.1.5 Other Types

Magnetic white dwarf: Grw +70°8247 [261]

Type description: Has detectable magnetic field; $\sim$ 10% of WDs have megaGauss fields and $\sim$ 10% are weakly magnetic with kiloGauss fields
Type references: Wickramasinghe & Ferrario (2000); Liebert et al. (2003); Landstreet et al. (2012)

Grw +70°8247 *is sidereal source*
Reason for selection of Grw +70°8247: Well-studied (most citations of Wickramasinghe & Ferrario 2000 review); first discovered
Works relating Grw +70°8247 to type: Kemp et al. (1970); Wickramasinghe & Ferrario (2000)

Pulsating white dwarf: ZZ Cet [262]

Type description: White dwarf with variability induced by non-radial g-mode pulsations
Notes on type: Includes the DAV/ZZ Ceti white dwarfs in the classical (He-opacity) instability strip; DBV white dwarfs in the iron-opacity (early-type) instability strip; variable hot and pre-white dwarfs, including pulsating PG 1159 white dwarfs and the DOV white dwarfs; pulsating ELM white dwarfs
Type references: Gautschy & Saio (1996); Winget & Kepler (2008); Althaus et al. (2010)

ZZ Cet *is sidereal source*
Reason for selection of ZZ Cet: Eponym of class of pulsating white dwarfs
Notes on ZZ Cet: DAV-type
Works relating ZZ Cet to type: Romero et al. (2012)

Blackbody white dwarfs: Ton 124 [263]

Type description: Apparently pure blackbody spectra; small subset of WDs spectral type DC
Type references: Suzuki & Fukugita (2018); Serenelli et al. (2019)

Ton 124 *is sidereal source*
Reason for selection of Ton 124: Nearest of Suzuki & Fukugita (2018) sample
Works relating Ton 124 to type: Serenelli et al. (2019)

Relationship to SETI: Small megastructures around hot stars are expected to have similar blackbody spectrum (Osmanov & Berezhiani 2018)

1.5.2 Neutron stars

Neutron stars are grouped primarily by their rotation rate and magnetic field. These parameters also control the emission we observe and are related to evolutionary state (e.g., Alpar et al. 1982; Olausen & Kaspi 2014).

Abbreviation for general class: NS

Compact Central Object: 1E 1207.4-5209 [264]

Abbreviations for type: CCO
Type description: X-ray sources within supernova remnants; thermal emission; no PWNe; possibly weak magnetic fields; some show rotational periodicity
Type references: Zavlin et al. (2000); Gotthelf et al. (2013)

1E 1207.4-5209 *is sidereal source*
Reason for selection of 1E 1207.4-5209: Most studied (Gotthelf & Halpern 2018)
General works about 1E 1207.4-5209: Giacani et al. (2000)

Alternative prototype(s): Cas A compact object – lacks pulsed emission (Pavlov et al. 2000)

Radio-quiet pulsar: Geminga [265]

Type description: Pulsar with pulsed gamma-ray emission but weak or no radio pulses; gamma-ray beams from different region of PSR magnetosphere, wider than radio beams
Relationship with other types: Radio-loud pulsar viewed off-axis
Type references: Abdo et al. (2009a); Caraveo (2014)

Geminga *is sidereal source*
Reason for selection of Geminga: Explicit prototype, well-cited, first discovered
Notes on Geminga: Radio-quiet but not radio-silent (Malofeev & Malov 1997); one of "Three Musketeers" ($\sim$ 0.1–1 Myr old, pulsed X-ray emission from polar hot spots) (Pavlov et al. 2002)
Works where Geminga referred to as prototype: Abdo et al. (2009a)
General works about Geminga: Faherty et al. (2007); Thompson et al. (1977); Abdo et al. (2010a)
Relationships between Geminga and other Exotica Catalog objects: Within the sky region occupied by: Geminga halo [379]

Radio-loud pulsar: Crab pulsar [266]

Type description: Restricted to unrecycled pulsars; radio pulses observed from rotationally modulated narrow radio beams; rotation periods: 0.1–10 s; dipole magnetic fields: 10^{11}–10^{13} G
Type references: Hewish et al. (1968); Bell Burnell (1977); Caraveo (2014)

Crab pulsar *is sidereal source*
Reason for selection of Crab pulsar: Most famous, well-studied, rich variety of pulsation behavior
Notes on Crab pulsar: Remnant of Crab Supernova, engine of Crab Nebula; pulses detected across spectrum; second most luminous known (Marshall et al. 1998)
Works relating Crab pulsar to type: Hankins et al. (2003); Cordes et al. (2004)
General works about Crab pulsar: Abdo et al. (2010b); Aliu et al. (2008); Boldt et al. (1969); Fierro et al. (1998); Lucarelli et al. (2008); Hester (2008); Cordes et al. (2004); Cocke et al. (1969); Hankins et al. (2003)
Relationships between Crab pulsar and other Exotica Catalog objects: Within the sky region occupied by: Crab Nebula [376]

Optical pulsar: Crab pulsar [266]

Type description: Pulsar from which periodic optical light is directly detected; modulated at the spin period; emission is intrinsic (magnetospheric) and not due to companion
Type references: Cocke et al. (1969); Wallace et al. (1977); Middleditch et al. (1987); Shearer et al. (1997); Lucarelli et al. (2008); Ambrosino et al. (2017)

Crab pulsar *is sidereal source*
Reason for selection of Crab pulsar: Most famous, well-studied, one of few examples known
Notes on Crab pulsar: Remnant of Crab Supernova, engine of Crab Nebula; pulses detected across spectrum; second most luminous known (Marshall et al. 1998)
Works relating Crab pulsar to type: Cocke et al. (1969); Lucarelli et al. (2008); Aliu et al. (2008)
General works about Crab pulsar: Abdo et al. (2010b); Aliu et al. (2008); Boldt et al. (1969); Fierro et al. (1998); Lucarelli

et al. (2008); Cordes et al. (2004); Hester (2008); Cocke et al. (1969); Hankins et al. (2003)

Relationships between Crab pulsar and other Exotica Catalog objects: Within the sky region occupied by: Crab Nebula [376]

Alternative prototype(s): Vela pulsar – much fainter (Wallace et al. 1977); PSR J1023+0038: first optically pulsing millisecond pulsar, elsewhere in catalog – much fainter, part of interacting (spider/XRB) system (Ambrosino et al. 2017)

Magnetar (radio quiet): SGR 1806-20 [267]

Type also known as: Soft gamma repeater (SGR); Anomalous X-ray pulsar (AXP)

Type description: NSs with extremely strong dipolar magnetic fields ($\sim 10^{14}$ G); long spin periods after spindown by magnetic fields; fields power enormous repeating gamma-ray flares; little to no pulsed radio emission

Type references: Duncan & Thompson (1992); Thompson & Duncan (1995); Kaspi & Beloborodov (2017)

SGR 1806-20 *is sidereal source*

Reason for selection of SGR 1806-20: Famous for extreme flare in 2004; most cited in Olausen & Kaspi (2014) catalog

Notes on SGR 1806-20: 2004 flare had highest gamma-ray flux of any outside Solar System

Works relating SGR 1806-20 to type: Hurley et al. (2005); Palmer et al. (2005); Terasawa et al. (2005)

General works about SGR 1806-20: Tendulkar et al. (2016); Kouveliotou et al. (1998); Olausen & Kaspi (2014)

Magnetar (radio loud): XTE J1810-197 [268]

Type description: NSs with extremely strong dipolar magnetic fields ($\sim 10^{14}$ G); fields power enormous repeating gamma-ray flares; sources of pulsed radio emission following outbursts

Type references: Camilo et al. (2006); Rea et al. (2012); Kaspi & Beloborodov (2017)

XTE J1810-197 *is sidereal source*

Reason for selection of XTE J1810-197: First discovered

Works relating XTE J1810-197 to type: Camilo et al. (2006)

Alternative prototype(s): 1E 1547-5408 – second discovered (Camilo et al. 2007); SGR J1745-2900: in Galactic Center (Eatough et al. 2013; Lynch et al. 2015), well-covered by Breakthrough Listen observations

Magnetar (fast radio burster): SGR 1935+2154 [269]

Type description: Magnetar that emits brilliant milisecond radio transients, easily visible from extragalactic distances

Type references: Popov & Postnov (2010); Platts et al. (2019); Bochenek et al. (2020); Dai & Zhong (2020)

SGR 1935+2154 *is sidereal source*

Reason for selection of SGR 1935+2154: First identified

Works relating SGR 1935+2154 to type: Scholz & Chime/Frb Collaboration (2020); Bochenek et al. (2020); Mereghetti et al. (2020)

General works about SGR 1935+2154: Mereghetti et al. (2020); Scholz & Chime/Frb Collaboration (2020); Bochenek et al. (2020)

Rotating radio transient: PSR B0656+14 [270]

Abbreviations for type: RRAT

Type description: Pulse sporadically in radio, minutes to hours between pulsed; rotation period: a few seconds; ages: $\sim$ 0.1–10 Myr

Type references: McLaughlin et al. (2006); Keane et al. (2011)

PSR B0656+14 *is sidereal source*

Reason for selection of PSR B0656+14: Closest likely example

Caveats about selection of PSR B0656+14: Regular faint pulses observed – would not be seen at distance of other RRATs

Notes on PSR B0656+14: One of "Three Musketeers" ($\sim$ 0.1–1 Myr old, pulsed X-ray emission from polar hot spots) (Pavlov et al. 2002)

Works relating PSR B0656+14 to type: Weltevrede et al. (2006)

General works about PSR B0656+14: Brisken et al. (2003)

X-ray Dim Isolated Neutron Star: RX J1856.5-3754 [271]

Abbreviations for type: XDINS
Type description: Detected only by thermal X-ray emission; characteristic spin-down ages: several Myr, may not be actual ages
Type references: Mignani et al. (2013)

RX J1856.5-3754 *is sidereal source*
Reason for selection of RX J1856.5-3754: Most cited of original seven discovered
Notes on RX J1856.5-3754: Has optical counterpart; pulsation period: 7 s; age: 0.4–4 Myr
Works relating RX J1856.5-3754 to type: Walter & Matthews (1997); Treves et al. (2000)
General works about RX J1856.5-3754: Mignani et al. (2013); Walter & Matthews (1997); Tiengo & Mereghetti (2007)

Millisecond pulsar: PSR J0437-4715 [272]

Abbreviations for type: MSP
Type description: Rotation period: 1.5–10 ms; form through binary evolution, angular momentum transfer during accretion during X-ray binary phase; radio and gamma-ray pulses; magnetic fields: $\sim 10^9$ G; spin-down times: $\gtrsim 100$ Myr
Type references: Alpar et al. (1982)

PSR J0437-4715 *is sidereal source*
Reason for selection of PSR J0437-4715: Nearest; highest radio flux; well-cited
Works relating PSR J0437-4715 to type: Johnston et al. (1993)
General works about PSR J0437-4715: Verbiest et al. (2008)

1.5.3 Stellar-mass black holes

Black holes are grouped by detection method. Only a few detached black holes are known with firm positions, and many candidates are disputed (e.g., El-Badry & Quataert 2020; van den Heuvel & Tauris 2020; Bodensteiner et al. 2020), constraining our choice of Prototypes.

Abbreviation for general class: BH

Accreting black hole: Cygnus X-1 [273]

Type description: In X-ray binary, detected by accretion luminosity; companion's orbital motion distinguishes from XRBs with neutron stars
Type references: Casares et al. (1992)

Cygnus X-1 *is sidereal source*
Cygnus X-1 also known as: HD 226868 (donor)
Reason for selection of Cygnus X-1: Extremely well-studied; first likely candidate; BH status confident; hosts ISM bubble elsewhere in catalog
Notes on Cygnus X-1: Mass: 10–20 $M_\odot$; companion is O supergiant ($\sim$ 20–30 $M_\odot$)
Works relating Cygnus X-1 to type: Webster & Murdin (1972); Oda (1977); Orosz et al. (2011); Ziolkowski (2014)
General works about Cygnus X-1: Webster & Murdin (1972); Stirling et al. (2001); Ziolkowski (2014); Orosz et al. (2011); Gallo et al. (2005); Oda (1977)
Relationships between Cyg X-1 and other Exotica Catalog objects: Within the sky region occupied by: Cygnus X-1 shell [384]

Detached black hole (globular cluster): NGC 3201 BH1 [274]

Type description: Black hole in detached binary system located in globular cluster; system has no significant mass transfer; currently detected by radial velocity perturbations of companion
Caveats about type: There have been several claims of detached black holes in the recent literature (Liu et al. 2019; Thompson et al. 2019; Rivinius et al. 2020), but most have been disputed. The disputed black holes have giant star companions, especially the blue giants LB-1 and QV Tel, where the objects appear to be helium stars (e.g., Eldridge et al. 2019; Simón-Díaz et al. 2020; El-Badry & Quataert 2020; Bodensteiner et al. 2020). The cool giant 2MASS J0521+4359 also has uncertain parameters

and its companion black hole is also disputed van den Heuvel & Tauris (2020); Thompson et al. (2020). El-Badry & Quataert (2020) considers this system the most likely true detached black hole, but notes that the evolutionary mechanism is different in dense globular clusters than in the field.
Type references: Giesers et al. (2018, 2019)

NGC 3201 BH1 *is sidereal source*
Reason for selection of NGC 3201 BH1: First discovered example, among most secure candidates for detached BH
Notes on NGC 3201 BH1: Mass: $\geq 4.56 \pm 0.21$ $M_{\odot}$; dwarf star companion
Works relating NGC 3201 BH1 to type: Giesers et al. (2018, 2019)

Failed supernova: NGC 6946-BH1 [275]

Type description: Black hole existence inferred when progenitor supergiant essentially vanishes with little to no explosion; young black hole, can be isolated; events are very rare
Type references: Kochanek et al. (2008); Gerke et al. (2015); Reynolds et al. (2015)

NGC 6946-BH1 *is sidereal source*
Reason for selection of NGC 6946-BH1: First candidate found
Works relating NGC 6946-BH1 to type: Gerke et al. (2015); Adams et al. (2017)
General works about NGC 6946-BH1: Adams et al. (2017); Gerke et al. (2015)
Works about host of NGC 6946-BH1: Anand et al. (2018a)
Relationships between NGC 6946-BH1 and other Exotica Catalog objects: Adjacent on sky to (sharing parent object with): SN 2008S [756]
Relationships between NGC 6946-BH1 and objects in I17: Within the sky region occupied by: NGC 6946

1.6 Interacting binary stars

A phylum describing the system of two stars where either the luminosity or the evolution is strongly affected by mass transfer of some kind. Substantial energy can be released through the process of accretion, nuclear burning on the surface of a recipient star, or by the collisions of stellar outflows.

Arguably, it could be split into at least two phyla: the accreting binary stars, and binary stars whose outflows interact.

We group interacting binary stars powered by accretion by the nature of the mass donor and that of the recipient.

1.6.1 Semidetached binary stars

Semidetached binaries are those in which one component fills its Roche lobe while the other does not, resulting in mass overflow from the one to the other. Neither component is a Collapsed star.

Algol-type binaries: Algol [276]

Type description: Mass recipient is dwarf star; little high-energy emission; accretion traced by Hα emission line; less massive donor may be at later evolutionary stage than recipient, in sign of mass transfer
Type references: Richards & Albright (1999); Budding et al. (2004)

Algol *is sidereal source*
Reason for selection of Algol: Explicit prototype; brightest; closest
Works where Algol referred to as prototype: Soderhjelm (1980); Richards (1992)
Works relating Algol to type: Richards (1992)
General works about Algol: Soderhjelm (1980)
Algol in I17

1.6.2 Contact binaries

Distinguished from true common envelope binaries, which have lifetimes of ~ 1 yr and are highly unstable (Paczynski 1976; Iben & Livio 1993).

General class also known as: Overcontact binary
General references: Lucy (1968); Mochnacki (1981)

Shallow overcontact binary: W UMa [277]

Type description: Overcontact binary with small f (0–0.5), where $f = 0$ is marginal contact; born as contact binary

W UMa *is sidereal source*

Reason for selection of W UMa: Explict prototype of all overcontact binaries

Notes on W UMa: f: 0.3 (Maceroni & van't Veer 1996; Pribulla et al. 2003), 0.1 (Csizmadia & Klagyivik 2004); W-type W UMa (Csizmadia & Klagyivik 2004)

Deep overcontact binary: FG Hya [278]

Type description: Overcontact binary with large f (0.5–1), wheree $f = 1$ becomes common-envelope binary; born as contact binary

FG Hya *is sidereal source*

Reason for selection of FG Hya: Second-most cited of Yang & Qian (2015); f relatively high (Yang & Qian 2015)

Notes on FG Hya: A-type W UMa (Csizmadia & Klagyivik 2004)

OO Aql contact binary: OO Aql [279]

Type description: Born detached, evolved into W UMa contact binary

Type references: Mochnacki (1981)

OO Aql *is sidereal source*

Reason for selection of OO Aql: Eponym

1.6.3 Symbiotic binaries

Consist of a cool giant star transferring mass (usually via wind) onto a small, hotter recipient. The recipient is frequently a white dwarf, but it can also be a star or even a neutron star. The giant usually donates mass via its wind.

General references: Belczyński et al. (2000)

S-type symbiotic binary: CH Cyg [280]

Type description: Donor is red giant; most common type

CH Cyg *is sidereal source*

Reason for selection of CH Cyg: Well-studied (third most cited of Belczyński et al. 2000 catalog; most cited within 300 pc); brightest

D-type symbiotic binary: R Aqr [281]

Type description: Donor is Mira-type AGB; sheathed in dust shells

Type references: Whitelock (1987)

R Aqr *is sidereal source*

Reason for selection of R Aqr: Well-studied (fourth most cited of Belczyński et al. (2000) catalog; closest after Mira itself; host elsewhere in catalog

Works relating R Aqr to type: Whitelock (1987)

Relationships between R Aqr and other Exotica Catalog objects: Within the sky region occupied by: R Aqr nebula [380]

Weakly symbiotic binary: Mira [216]

Type description: Recipient ionizes small bubble in donor giant's wind; low mass transfer rate; seems to have minimal effect on donor itself

Mira *is sidereal source*

Reason for selection of Mira: Very well-cited; Mira A elsewhere in catalog

Notes on Mira: Referred to as "symbiotic-like", "weakly symbiotic" (Sokoloski & Bildsten 2010), and "mildly symbiotic" (Chandler et al. 2007)

Works relating Mira to type: Ramstedt et al. (2014); Vlemmings et al. (2015)

General works about Mira: Sokoloski & Bildsten (2010); Chandler et al. (2007); Vlemmings et al. (2015); Ramstedt et al. (2014); Wong et al. (2016)

Symbiotic nova: RR Tel [282]

Type also known as: Slow nova
Type description: Symbiotic system undergoing decades-long event; rises 2–7 magnitudes initially before very slowly decaying; eruption type unique to symbiotic binaries; appear to be result of thermonuclear burning on WD surface
Type references: Allen (1980); Murset & Nussbaumer (1994)

RR Tel *is sidereal source*
Reason for selection of RR Tel: Explicit prototype; well-studied
Works where RR Tel referred to as prototype: Allen (1980)
General works about RR Tel: Selvelli et al. (2007)

Supersoft Source (symbiotic): RR Tel [282]

Abbreviations for type: SSS; SXS
Type description: Nuclear burning on white dwarf surface leads to bright thermal emission with temperature 15–80 eV
Notes on type: Is subclass of Supersoft X-ray sources
Type references: Kahabka & van den Heuvel (1997)

RR Tel *is sidereal source*
Reason for selection of RR Tel: Well-studied (most cited symbiotic SSS in Kahabka & van den Heuvel 1997); consistent symbiotic classification in Kahabka & van den Heuvel (1997) and Šimon (2003)
General works about RR Tel: Selvelli et al. (2007); Allen (1980)

Symbiotic recurrent nova: RS Oph [283]

Type description: System has repeated novae of typical characteristics from unstable nuclear burning on WD companion surface; neither component has overflowing Roche lobe
Type references: Iben (2003); Schaefer (2010); Kato et al. (2012)

RS Oph *is sidereal source*
Reason for selection of RS Oph: Explicit prototype; well-studied (most citations of Schaefer 2010)
Notes on RS Oph: Eight observed outbursts, most recently in 2006
Works where RS Oph referred to as prototype: Hachisu & Kato (2001); Shore et al. (2011)
Works relating RS Oph to type: Shore et al. (2011)

1.6.4 Cataclysmic Variables

Consist of a G, K, M, or brown dwarf donor and white dwarf accretor, where mass transfer occurs through Roche lobe overflow. A diverse class, where the different subtypes mark different regimes in accretion rate and WD magnetic field. Several subtypes are characterized by sudden outbursts. They are divided by variability/eruption characteristics (Osaki 1996; Schaefer 2010) and white dwarf magnetic field interaction with the accretion disk (Patterson 1994).

Abbreviation for general class: CV

General references: Patterson (1984); Kolb & Baraffe (1999); Knigge (2006); Littlefair et al. (2006); Gänsicke et al. (2009)

Dwarf nova: SS Cyg [284]

Type description: CV with relatively small (2–6 magnitudes) but frequent (every few weeks or months) outbursts; likely caused by state change in accretion disk heat transport; WD lacks strong magnetic field
Type references: Meyer & Meyer-Hofmeister (1981); Smak (1984); Osaki (1996); Lasota (2001)

SS Cyg *is sidereal source*
Reason for selection of SS Cyg: Explict prototype; brightest on sky; well-studied
Works where SS Cyg referred to as prototype: Osaki (1996); Nelan & Bond (2013)

Works relating SS Cyg to type: Smak (1984); Wheatley et al. (2003)
General works about SS Cyg: Nelan & Bond (2013)

Novalike variable: UX UMa [285]

Type description: Inversion of dwarf novae; accretion disk normally stuck in high-luminosity state found in dwarf nova outburst; occasional dips possible; WD lacks strong magnetic field
Notes on type: The VY Scl subclass displays anti-dwarf novae when it fades more than 1 magnitude into low-luminosity states, comparable to the "normal" state of dwarf novae (Dhillon 1996; King & Cannizzo 1998; Leach et al. 1999; Honeycutt & Kafka 2004)
Type references: Warner (1976); Baptista et al. (1995); Dhillon (1996); Leach et al. (1999); Noebauer et al. (2010); Neustroev et al. (2011); Hoard et al. (2014)

UX UMa *is sidereal source*
Reason for selection of UX UMa: Explicit prototype; brightest on sky
Works where UX UMa referred to as prototype: Osaki (1996); Neustroev et al. (2011)
General works about UX UMa: Noebauer et al. (2010)

Alternative prototype(s): MV Lyr – well-studied example of anti-dwarf nova (VY Scl) system (Honeycutt & Kafka 2004)

Recurrent nova (CV): T Pyx [286]

Type description: CVs where sudden bursts of nuclear fusion occur within matter accreted on WD; happens repeatedly
Notes on type: All novae thought to be recurrent on long timescales, but here reserved for those that repeat within decades

T Pyx *is sidereal source*
Reason for selection of T Pyx: Implicit prototype; well-studied
Works where T Pyx referred to as prototype: Patterson et al. (2017)
Works relating T Pyx to type: Webbink et al. (1987); Downes et al. (1997); Schaefer (2010); Patterson et al. (2017)

Old classical nova: GK Per [287]

Type description: CVs where sudden bursts of nuclear fusion occur within matter accreted on WD; happens once or very rarely
Notes on type: All novae thought to be recurrent on long timescales, but here reserved for those that repeat over centuries or longer
Type references: Gallagher & Starrfield (1978); Seaquist et al. (1980); Hachisu & Kato (2006); Ackermann et al. (2014)

GK Per *is sidereal source*
GK Per also known as: Nova Persei 1901
Reason for selection of GK Per: Well-studied; remnant nebula elsewhere in catalog
Notes on GK Per: Is an intermediate polar CV
General works about GK Per: Evans et al. (2009); Watson et al. (1985)
Relationships between GK Per and other Exotica Catalog objects: Within the sky region occupied by: GK Per shell [381]

Intermediate polar: DQ Her [288]

Type also known as: DQ Her system
Type description: Magnetic field has sufficient strength to wrench matter from inner region of accretion disk; frequently though not always quickly rotating
Type references: Patterson (1994); Hellier (1999); Wickramasinghe & Ferrario (2000); Piirola et al. (2008)

DQ Her *is sidereal source*
Reason for selection of DQ Her: Eponym; well-studied

Intermediate polar propeller system: AE Aqr [289]

Type description: Magnetic field of rapidly spinning white dwarf flings matter out of system; spinning down
Type references: Wynn et al. (1997)

AE Aqr *is sidereal source*
Reason for selection of AE Aqr: Known example
Caveats about selection of AE Aqr: Ikhsanov (1998) instead proposes emission is due to pulsar-like spindown
Notes on AE Aqr: Rotation period: 33 seconds, fastest of any magnetic WD; has optical and X-ray oscillations; spindown observed
Works relating AE Aqr to type: Wynn et al. (1997); Blinova et al. (2019)
General works about AE Aqr: Ikhsanov (1998); Patterson et al. (1980); Kitaguchi et al. (2014); Patterson (1994, 1979)

Polar: AM Her [290]

Type also known as: AM Her system
Type description: CV with strongly magnetic WD ($\gtrsim$ 10 MG); magnetic field lines channel accreting material onto WD poles before it can form any accretion disk
Type references: Cropper (1990); Patterson (1994); Schmidt et al. (1996); Wickramasinghe & Ferrario (2000)

AM Her *is sidereal source*
Reason for selection of AM Her: Eponym; nearest example

Cataclysmic variable pulsar: AR Sco [291]

Type description: Displays pulsations in radio through X-ray bands, once per spin period; pulses are strongly linearly polarized, weakly circularly polarized; predicted to arise from interaction of WD's wind or magnetic field with M dwarf companion

AR Sco *is sidereal source*
Reason for selection of AR Sco: Known example
Caveats about selection of AR Sco: White dwarf may be displaying pulsar phenomena independent of companion (Buckley et al. 2018)
Works relating AR Sco to type: Marsh et al. (2016); Geng et al. (2016); Buckley et al. (2017); Takata et al. (2018); Buckley et al. (2018); Garnavich et al. (2019)

1.6.5 AM CVn binaries

Closely related to cataclysmic variables, except the donor is a helium star or white dwarf.

AM CVn system: AM CVn [292]

Type description: Small, helium-rich donor star (white dwarf or helium star) with WD recipient; mass transfer from Roche lobe overflow; very compact, with orbital periods $\lesssim$ 1 hr
Type references: Nelemans (2005); Roelofs et al. (2007); Solheim (2010)

AM CVn *is sidereal source*
Reason for selection of AM CVn: Eponym; first discovered
Works relating AM CVn to type: Roelofs et al. (2007)
General works about AM CVn: Roelofs et al. (2007)

1.6.6 Close binary supersoft X-ray sources

Closely related to cataclysmic variables, except the donor is a subgiant, somewhat more massive than CV donors.

Close binary supersoft X-ray source: QR And [293]

Abbreviations for type: SSS; SSX
Type also known as: Classical supersoft X-ray source; subgiant supersoft X-ray source
Type description: Consist of end-main sequence or subgiant donors (mass: 1.3–2.5 $M_\odot$) and less massive white dwarf companion; steady nuclear burning on WD surface leads to 15–80 eV thermal X-rays; luminosity: 10^{36}–10^{38} $L_\odot$
Type references: Yungelson et al. (1996); Kahabka & van den Heuvel (1997); Šimon (2003)

QR And *is sidereal source*
Reason for selection of QR And: Well-studied (most cited of Kahabka & van den Heuvel 1997 review); first known Galactic

example; one of closest and brightest
Works relating QR And to type: Beuermann et al. (1995)
General works about QR And: McGrath et al. (2001)

1.6.7 X-ray Binaries

Interacting binaries where a neutron star or a black hole are accreting matter from a donor, resulting in prodigious X-ray emission. Some are among the most luminous objects in a galaxy. An extremely diverse class (see Table 1 of Reig 2011). They are classified according to the type of compact object and the mass of the donor. Still finer divisions specify the mode of mass transfer and other characteristics (see especially Reig 2011; Kaaret et al. 2017). X-ray binaries with an extreme super-Eddington accretion rate or luminosity (including the ultraluminous X-ray sources) are given their own special subcategory. Two more empirical types where the recipient's nature is indeterminate round out the category.

Abbreviation for general class: XRBs
General references: Grimm et al. (2002); Fabbiano (2006); Reig (2011); Kaaret et al. (2017)

1.6.7.1 Neutron star X-ray binaries

Neutron star XRBs are distinct because they have a surface. This results in a hot boundary or spreading layer where matter settles on the surface accounting that can account for the majority of the luminosity (Syunyaev & Shakura 1986; Inogamov & Sunyaev 1999; Popham & Sunyaev 2001; Gilfanov et al. 2003; Revnivtsev & Gilfanov 2006). It also allows them to host Type I bursts as the settled matter undergoes unstable nuclear burning (Lewin et al. 1993; Schatz et al. 1999; Cumming & Bildsten 2001; Strohmayer & Brown 2002; Galloway et al. 2008; in't Zand et al. 2019).

1.6.7.1.1 Neutron star Low mass X-ray binaries

Abbreviation for general class: LMXB
General references: Hasinger & van der Klis (1989)

Z source: Sco X-1 [294]

Type description: LMXB with high mass accretion rate; traces out three connected branches (in "Z" shape) when different epochs of variable X-ray emission is plotted on color-color diagram
Type references: Hasinger & van der Klis (1989); van der Klis (1989)

Sco X-1 *is sidereal source*
Reason for selection of Sco X-1: Confident Z-source; well-studied; first discovered XRB; second brightest on sky; second most luminous NS-LMXB in Galaxy
Works relating Sco X-1 to type: van der Klis (1989)
General works about Sco X-1: Grimm et al. (2002)

Atoll source: 4U 1608-52 [295]

Type description: LMXB with low mass accretion rate; wanders chaotically in color-color diagram, can trace out fuzzy arc shape ("banana" state) or skip between disjoint cluster ("island" state), depending on accretion state
Type references: Hasinger & van der Klis (1989)

4U 1608-52 *is sidereal source*
4U 1608-52 also known as: Norma Burster
Reason for selection of 4U 1608-52: Well-studied (most cited in Hasinger & van der Klis 1989; second most cited of Muno et al. 2002), although mostly due to frequent Type I bursts
General works about 4U 1608-52: van Straaten et al. (2003)

Type II Burster: 4U 1730-335 [296]

Type description: Has rapid outbursts caused by accretion instabilities, which last seconds and may recur several times a minute
Type references: Lewin et al. (1993); Kouveliotou et al. (1996); Court et al. (2018)

4U 1730-335 *is sidereal source*
4U 1730-335 also known as: Rapid Burster
Reason for selection of 4U 1730-335: One of two known examples; first discovered
Works relating 4U 1730-335 to type: Lewin et al. (1976); Hoffman et al. (1978); Lewin et al. (1993)

Ultracompact low-mass X-ray binary: 4U 1820-303 [297]

Abbreviations for type: UCXB
Type description: Donor is helium star or white dwarf; orbital period $\lesssim 1$ hr
Type references: Belczynski & Taam (2004); in't Zand et al. (2007); van Haaften et al. (2013)

4U 1820-303 *is sidereal source*
Reason for selection of 4U 1820-303: Well-studied (most cited of confident UCXBs in in't Zand et al. 2007), partly because of its superbursts
Works relating 4U 1820-303 to type: Stella et al. (1987)
General works about 4U 1820-303: Strohmayer & Brown (2002)

Symbiotic low-mass X-ray binary: GX 1+4 [298]

Abbreviations for type: SyXRB
Type description: Donor is cool giant star; mass transfer through giant star's stellar wind; system appears like symbiotic star
Type references: Chakrabarty & Roche (1997); Masetti et al. (2006); van den Eijnden et al. (2018a)

GX 1+4 *is sidereal source*
Reason for selection of GX 1+4: First known example with M giant donor, although FG giant donors were known earlier
Works relating GX 1+4 to type: Chakrabarty & Roche (1997); van den Eijnden et al. (2018a)

Accreting Millisecond Pulsar: SAX J1808.4-3658 [299]

Abbreviations for type: AMXP
Type description: Accreting NS spin period < 0.01 s, being spun up (recycled) by accretion process; X-ray pulsations
Type references: Alpar et al. (1982); Patruno & Watts (2012)

SAX J1808.4-3658 *is sidereal source*
Reason for selection of SAX J1808.4-3658: First discovered
General works about SAX J1808.4-3658: Chakrabarty & Morgan (1998); Wijnands & van der Klis (1998); Galloway & Cumming (2006)

Transitional millisecond pulsar: PSR J1023+0038 [300]

Abbreviations for type: TMP
Type description: Switches back and forth between appearing as X-ray binary to radio millisecond pulsar; competition between inflowing accretion and outflowing pulsar wind
Type references: Papitto et al. (2013); Veledina et al. (2019)

PSR J1023+0038 *is sidereal source*
Reason for selection of PSR J1023+0038: Well-studied; first discovered; state changes in both direction observed
Notes on PSR J1023+0038: Transitioned from XRB to radio-MSP sometime after 2001; transitioned back to XRB in 2014; first optical pulsating MSP
Works relating PSR J1023+0038 to type: Archibald et al. (2009); Stappers et al. (2014); Patruno et al. (2014); Ambrosino et al. (2017); Hui & Li (2019)
General works about PSR J1023+0038: Roberts (2013); Archibald et al. (2009); Stappers et al. (2014); Hui & Li (2019); Roberts (2011); Ambrosino et al. (2017); Patruno et al. (2014)

1.6.7.2 Neutron star intermediate mass X-ray binaries

Neutron star Intermediate Mass X-ray binary: Her X-1 [301]

Abbreviations for type: NS IMXB
Type description: Donor is star with mass $\sim$ 2–6 $M_\odot$; mass transfer through Roche lobe overflow
Notes on type: Generally thought to be unstable to mass transfer (Tauris et al. 2000), but may be stable for donor masses up to 4 $M_\odot$ in some circumstances (Podsiadlowski et al. 2002); may be progenitors of some LMXBs (Podsiadlowski & Rappaport 2000)
Type references: Podsiadlowski & Rappaport (2000); Podsiadlowski et al. (2002); Pfahl et al. (2003); Xu & Li (2007); Karino (2016)

Her X-1 *is sidereal source*
Her X-1 also known as: HZ Her
Reason for selection of Her X-1: Known example; very well studied
Notes on Her X-1: Donor mass: 2.15–2.20 $M_\odot$ or 2.35–2.45 $M_\odot$ (Leahy & Abdallah 2014)
Works relating Her X-1 to type: van den Eijnden et al. (2018b)
General works about Her X-1: Gerend & Boynton (1976); Leahy & Abdallah (2014)

1.6.7.3 Neutron star High mass X-ray binaries

High mass X-ray binaries tend to be dimmer than LMXBs. They are classified based on the type of donor and mass transfer.

General references: Reig (2011); Walter et al. (2015)

Neutron star Be/X-ray binary: A 0535+26 [302]

Type description: Donors are Oe or Be dwarfs, subgiants or giants; outflow feeding NS is decretion disk flung off rapidly rotating donor; accretion when NS near or piercing disk; most common type; usually intermittent because NS has eccentric orbit
Type references: Reig (2011)

A 0535+26 *is sidereal source*
A 0535+26 also known as: V725 Tau; HD 245770
Reason for selection of A 0535+26: Well-studied (second most cited of Reig 2011); transient nature is representative
Works relating A 0535+26 to type: Camero-Arranz et al. (2012)

Alternative prototype(s): X Per: most cited of Reig (2011), explicit prototype of rare persistent subclass

Classical supergiant neutron star X-ray binary: Vela X-1 [303]

Type description: Supergiant donor star; mass transfer from capture of wind by NS

Vela X-1 *is sidereal source*
Reason for selection of Vela X-1: Explicit prototype
Works where Vela X-1 referred to as prototype: Walter et al. (2015)

Roche-lobe overflow HMXB: Cen X-3 [304]

Type description: Supergiant donor star; mass stripped off by NS through Roche lobe overflow; very rare

Cen X-3 *is sidereal source*
Reason for selection of Cen X-3: Only known Galactic example
Works relating Cen X-3 to type: Walter et al. (2015)

Symbiotic high-mass X-ray binary: 4U 1954+31 [305]

Type description: Donor is massive cool supergiant star; mass transfer through supergiant star's stellar wind; system appears like symbiotic star
Type references: Hinkle et al. (2020)

4U 1954+31 *is sidereal source*
Reason for selection of 4U 1954+31: First known example
Notes on 4U 1954+31: Previously classified as symbiotic LMXB with M giant donor (Mattana et al. 2006); Hinkle et al. (2020)

argues that spectrum and *Gaia* parallax implies brighter supergiant donor
Works relating 4U 1954+31 to type: Hinkle et al. (2020)

1.6.7.4 Black hole X-ray binaries

General references: Remillard & McClintock (2006)

Black hole LMXB: V404 Cyg [306]

Type description: Donor is late-type dwarf; mass transfer is through Roche-lobe overflow into accretion disk; almost always transient, probably because of disk instabilities
Type references: Tanaka & Shibazaki (1996); Menou et al. (1999); Remillard & McClintock (2006); Bernardini & Cackett (2014)

V404 Cyg *is sidereal source*
Reason for selection of V404 Cyg: Explicit prototype; well-studied (fourth most cited of Remillard & McClintock 2006 review) because relatively bright during quiescence; first confirmed as a BH recipient
Works where V404 Cyg referred to as prototype: Oates et al. (2019)
Works relating V404 Cyg to type: Casares et al. (1992); Menou et al. (1999); Remillard & McClintock (2006); Khargharia et al. (2010); Bernardini & Cackett (2014)
General works about V404 Cyg: Miller-Jones et al. (2009)

Alternative prototype(s): Mon X-1: closer, also well-studied, also explicit prototype (Foellmi 2009)

Black hole Be/X-ray binary: MCW 656 [307]

Type description: Donors are Oe or Be dwarfs, subgiants or giants; outflow feeding BH is decretion disk flung off rapidly rotating donor; accretion when BH near or piercing disk

MCW 656 *is sidereal source*
Reason for selection of MCW 656: Known example
Works relating MCW 656 to type: Casares et al. (2014)

Supergiant black hole X-ray binary: Cygnus X-1 [273]

Type description: Supergiant donor star; mass transfer from capture of wind by BH; can be persistent, but accretion disk switches between different luminosities and spectral hardness
Type references: Remillard & McClintock (2006); Postnov & Yungelson (2014); Tetarenko et al. (2016)

Cygnus X-1 *is sidereal source*
Reason for selection of Cygnus X-1: Confirmed Galactic example; elsewhere in catalog
Works relating Cygnus X-1 to type: Oda (1977); Stirling et al. (2001); Ziolkowski (2014)
General works about Cygnus X-1: Webster & Murdin (1972); Gallo et al. (2005); Stirling et al. (2001); Ziolkowski (2014); Orosz et al. (2011); Oda (1977)
Relationships between Cyg X-1 and other Exotica Catalog objects: Within the sky region occupied by: Cygnus X-1 shell [384]

1.6.7.5 Microquasars

Microquasar: GRS 1915+105 [308]

Type description: Bright XRB launching relativistic jet; physics analogous to AGNs
Type references: Mirabel & Rodríguez (1998, 1999); Fomalont et al. (2001); Merloni et al. (2003)

GRS 1915+105 *is sidereal source*
Reason for selection of GRS 1915+105: Explicit prototype; jets are fast
Notes on GRS 1915+105: Apparent jet speed: 1.2–1.7c; actual speed: $> 0.8c$
Works where GRS 1915+105 referred to as prototype: McClintock et al. (2006)
Works relating GRS 1915+105 to type: Mirabel & Rodríguez (1994)
General works about GRS 1915+105: Reid et al. (2014)

1.6.7.6 Supercritical X-ray binaries

X-ray binaries accreting a rate faster than allowed by the Eddington limit (luminosity limit of $\sim 10^{38}$ erg s$^{-1}(M/\mathrm{M}_\odot)$, where M is the recipient mass). How this accretion rate is maintained persistently is unclear. Most of the different subtypes given here may actually represent the same type of object viewed at different angles (Begelman et al. 2006a; Pinto et al. 2017).

General references: Kaaret et al. (2017)

Faint supercritical X-ray binary: SS433 [309]

Type description: Supercritical XRB that appears faint in X-rays, with most of power hidden in kinetic energy of jets; luminosity inferred from jet-driven bubbles surrounding it

Type references: Fabrika (2004); Kaaret et al. (2017)

SS433 *is sidereal source*

Reason for selection of SS433: Known Galactic example; bubbles (W50) elsewhere in catalog

Notes on SS433: Kinetic power: $\sim 10^{40}$ erg s^{-1}; X-ray luminosity: 10^{36} erg s^{-1}; jet speed: $0.26c$; jets twist into helixes; may be ULX when viewed from different angle; accreting body likely a BH

Works relating SS433 to type: Fabrika (2004); Begelman et al. (2006a); Middleton et al. (2018); Waisberg et al. (2019); Khabibullin & Sazonov (2019)

General works about SS433: Fabrika (2004); Cherepashchuk et al. (2019); Marshall et al. (2013); Margon (1984); Bowler (2018)

Relationships between SS433 and other Exotica Catalog objects: Within the sky region occupied by: W50 [386]

Non-pulsating Ultraluminous X-ray source: M82 X-1 [310]

Abbreviations for type: ULX

Type description: Very luminous X-ray source (EIRP $> 10^{39}$ erg s^{-1}); no pulsations observed; recipient may be either NS or stellar-mass BH (or possibly intermediate-mass BH in some cases)

Type references: Fabrika et al. (2015); Kaaret et al. (2017)

M82 X-1 *is sidereal source*

Reason for selection of M82 X-1: Well-studied (most cited in Swartz et al. 2004; Feng & Soria 2011)

Notes on M82 X-1: Luminosity (EIRP): $\sim 10^{41}$ erg s^{-1} (peak); not to be confused with M82 X-2

Works relating M82 X-1 to type: Pasham et al. (2014); Greene et al. (2019); Brightman et al. (2020)

Works about host of M82 X-1: Dalcanton et al. (2009)

Relationships between M82 X-1 and other Exotica Catalog objects: Within the sky region occupied by: M82 [428]; Adjacent on sky to (sharing parent object with): 43.78+59.3 [745], M82 X-2 [312]

Supersoft ultraluminous X-ray source: M101 ULX-1 [311]

Abbreviations for type: ULS

Type description: Extremely bright (EIRP $> 10^{39}$ erg s^{-1}) supersoft source; X-ray emission is thermal and cool (< 100 eV); may be ULXs viewed through optically thick wind

Type references: Di Stefano & Kong (2003); Kong & Di Stefano (2003); Kong et al. (2004); Urquhart & Soria (2016); Pinto et al. (2017)

M101 ULX-1 *is sidereal source*

Reason for selection of M101 ULX-1: Explicit prototype; first ultraluminous example

Notes on M101 ULX-1: Wolf-Rayet–stellar mass BH binary according to Liu et al. (2013)

Works relating M101 ULX-1 to type: Di Stefano & Kong (2003); Liu et al. (2013)

Works about host of M101 ULX-1: Beaton et al. (2019)

Relationships between M101 ULX-1 and other Exotica Catalog objects: Within the sky region occupied by: M101 [414]

Ultraluminous X-ray pulsars: M82 X-2 [312]

Abbreviations for type: ULXP

Type description: Luminous (EIRP $> 10^{39}$ erg s^{-1}) X-ray source; has periodic pulsations due to spinning neutron star recipient;

occasionally enter months-long “off states”
Type references: Bachetti et al. (2014); Tsygankov et al. (2016); Bachetti et al. (2020)

M82 X-2 *is sidereal source*
Reason for selection of M82 X-2: Well-studied; first recognized
Notes on M82 X-2: Luminosity: 10^{40} erg s^{-1} (bright states); not to be confused with M82 X-1
Works relating M82 X-2 to type: Bachetti et al. (2014)
Works about host of M82 X-2: Dalcanton et al. (2009)
Relationships between M82 X-2 and other Exotica Catalog objects: Within the sky region occupied by: M82 [428]; Adjacent on sky to (sharing parent object with): 43.78+59.3 [745], M82 X-1 [310]

Globular cluster ultraluminous X-ray source: RZ 2109 ULX [313]

Type description: ULX located in a globular cluster, necessarily resulting from an older stellar populations unlike most other ULXs
Type references: Maccarone et al. (2007); Dage et al. (2020)

RZ 2109 ULX *is sidereal source*
Reason for selection of RZ 2109 ULX: Relatively well-studied; first detected
Notes on RZ 2109 ULX: Located in M49 (NGC 4472); peak X-ray luminosity: 4×10^{39} erg s^{-1}; suspected black hole
Works relating RZ 2109 ULX to type: Maccarone et al. (2007); Zepf et al. (2008); Joseph et al. (2015); Dage et al. (2018); Stiele & Kong (2019)
Relationships between RZ 2109 ULX and other Exotica Catalog objects: Within the sky region occupied by: Virgo Cluster [506]
Relationships between RZ 2109 ULX and objects in I17: Within the sky region occupied by: M49

1.6.7.7 Indeterminate XRBs

This category contains other XRBs where the nature of the accreting body is unknown

γ Cas X-ray binaries: γ Cas [314]

Type description: Peculiar Be XRBs, abnormally X-ray faint for an XRB, abnormally X-ray bright for star; lack HMXB variability, but have HMXB-like spectra; recipient nature unclear: could be NS, WD, or helium star
Type references: White et al. (1982); Murakami et al. (1986); Haberl (1995); Reig (2011); Postnov et al. (2017); Langer et al. (2020)

γ Cas *is sidereal source*
Reason for selection of γ Cas: Eponym

Supergiant Fast X-ray Transient: IGR J17544-2619 [315]

Abbreviations for type: SFXT
Type description: HMXB visible mainly through hours-long X-ray flares; recipients not always known, but some are probably NSs
Type references: Sguera et al. (2006); Drave et al. (2012)

IGR J17544-2619 *is sidereal source*
Reason for selection of IGR J17544-2619: Explicit prototype; well-studied (most cited of Sguera et al. 2006)
Notes on IGR J17544-2619: Has pulsations indicative of NS accretor
Works where IGR J17544-2619 referred to as prototype: Sidoli et al. (2008); Farinelli et al. (2012)
Works relating IGR J17544-2619 to type: Sguera et al. (2006); Drave et al. (2012)

1.6.8 Outflow interacting binaries

Interacting binaries where the system luminosity or spectrum is modified by outflow of one component interacting with the other component, typically at shocks.

1.6.8.1 Wind shock binaries

Colliding wind binary: WR 140 [316]

Abbreviations for type: CWB

Type description: Two massive early-type stars undergoing mass loss blast each other with stellar winds; impact at collisionless termination shock; shine brightly in radio and X-rays

Type references: Cherepashchuk (1976); Stevens et al. (1992a); Eichler & Usov (1993)

WR 140 *is sidereal source*

Reason for selection of WR 140: Explict prototype; well-studied

Notes on WR 140: Primary: Wolf-Rayet; secondary: O-type star; orbit is highly eccentric, with maximum interaction at periastron; shock directly imaged in VLBA radio images

Works where WR 140 referred to as prototype: Marchenko et al. (2003); Dougherty et al. (2005); Pittard & Dougherty (2006); Monnier et al. (2011)

Works relating WR 140 to type: Williams et al. (1990); Dougherty et al. (2005)

General works about WR 140: Monnier et al. (2011)

Iron star: XX Oph [317]

Type description: System of Be star and late (super-)giant identified by low ionization metal lines including iron; metal lines due to interaction of Be and cool giant outflows

Caveats about type: Nature of components in these systems may not be certain, although it definitely contains an M giant and a B star (Evans et al. 2012a)

Notes on type: The other likely example is AS 325; StHA 169 may be a third, but could be a symbiotic star (Ramsay et al. 2014)

Type references: Cool et al. (2005); Howell et al. (2009)

XX Oph *is sidereal source*

Reason for selection of XX Oph: Eponym (Merrill 1924); first discovered; one of few known examples

Works relating XX Oph to type: Cool et al. (2005)

General works about XX Oph: Evans et al. (2012a); Howell et al. (2009)

Alternative prototype(s): AS 325: second known example

Pulsar wind gamma-ray binaries: PSR B1259-63 [318]

Type description: Pulsar wind reaches termination shock in wind of early-type companion; most luminosity in form of gamma-rays emitted by particles accelerated at shock; may be progenitors of HMXBs

Type references: Aharonian et al. (2005); Dubus (2013)

PSR B1259-63 *is sidereal source*

Reason for selection of PSR B1259-63: Well-studied (second most cited of five systems in Dubus 2013); definitely has a pulsar

Works relating PSR B1259-63 to type: Dubus (2013)

General works about PSR B1259-63: Johnston et al. (1992)

1.6.8.2 Spider pulsars

Binary systems in which pulsar wind ablates companion. In some extreme cases, the companion is whittled away to a planet-mass object, and it is suspected that some MSPs have blown away their partner entirely. They are classified according to the type of partner.

General references: Fruchter et al. (1988); Kluzniak et al. (1988); Bailes et al. (2011); Dubus (2013); Roberts (2013); Hui & Li (2019)

Black widow system: PSR B1957+20 [319]

Type description: Companion is degenerate object with mass < 0.05 $M_\odot$ (brown dwarf-like), likely result of larger star; may be systems in which ablation is particularly effective because beamed pulsar wind directly hit partner

Type references: Chen et al. (2013)

PSR B1957+20 *is sidereal source*

PSR B1957+20 also known as: The Black Widow Pulsar

Reason for selection of PSR B1957+20: Original discovery

Notes on PSR B1957+20: Is eclipsing binary; wind off companion also produces plasma lenses that occasionally enhance pulsar's brightness

Works relating PSR B1957+20 to type: Fruchter et al. (1988); Kluzniak et al. (1988)
General works about PSR B1957+20: van Kerkwijk et al. (2011); Huang et al. (2012)
Relationships between PSR B1957+20 and other Exotica Catalog objects: Within the sky region occupied by: PSR B1957+20 bow shock [378]

Redback: PSR J1023+0038 [300]

Type description: Companion is somewhat inflated low-mass dwarf star with mass 0.2–0.4 $M_{\odot}$; at least some are still accreting episodically as transitional millisecond pulsars
Type references: Roberts (2013); Linares (2014); Torres et al. (2017); Strader et al. (2019)

PSR J1023+0038 *is sidereal source*
Reason for selection of PSR J1023+0038: Explicit prototype; one of first discovered; well-studied as TMP (most cited of Torres et al. 2017; Strader et al. 2019); elsewhere in catalog
Works where PSR J1023+0038 referred to as prototype: Roberts (2013)
Works relating PSR J1023+0038 to type: Roberts (2011); Hui & Li (2019)
General works about PSR J1023+0038: Archibald et al. (2009); Stappers et al. (2014); Roberts (2011); Ambrosino et al. (2017); Hui & Li (2019); Patruno et al. (2014)

Huntsman: PSR J1417-4402 [320]

Type description: Companion is low-mass giant star; proposed progenitor of typical MSP systems with WD companion on wide orbit
Type references: Camilo et al. (2016); Swihart et al. (2017b); De Vito et al. (2019)

PSR J1417-4402 *is sidereal source*
Reason for selection of PSR J1417-4402: First identified example
Works relating PSR J1417-4402 to type: Strader et al. (2015); Camilo et al. (2016); Swihart et al. (2017b, 2018)

1.7 Stellar groups

A phylum covering collections of "stars" that interact through gravity alone. They can be divided into hierarchical groups like multiple stars, non-hierarchical bound groups like star clusters, and unbound groups like stellar associations. Unlike galaxies, they do not display any evidence for dark matter (or non-Newtonian gravity). In this section, "star" can refer to substellar objects and collapsed stars.

The largest globular clusters overlap in size with ultracompact dwarf galaxies in the Galaxies phylum, and the distinction has some ambiguity.

1.7.1 Detached binary and multiple stars

Eggleton & Tokovinin (2008) proposes that multiple systems are distinguished from star clusters by their hierarchical nature. Defined this way, true multiples are generally built up of a small number of smaller multiple systems, generally in pairwise combinations, with single stars as the basic unit. That is, systems with multiplicity greater than 2 usually can be broken down into nested binaries and singletons. In contrast, all of the many stars in a cluster are bound to each other collectively.

We include non-interacting binary and multiple stars with other stellar groups like star clusters. As in Eggleton & Tokovinin (2008), they are distinguished from clusters by their hierarchical organization. Binary systems are well represented in the I17 catalog, and we do not try to capture all combinations of stellar types or separations. We specifically include double degenerate systems, however, which are not included in I17, and have the potential to be sites of ETI activity (Dyson 1963). A few binaries classified by how they are detected from Earth (heartbeat, eclipsing, self-lensing, chromospherically active) are included when they indicate distinct physical phenomena could be exploited for observation coordination by ETIs; visual, astrometric, photometric, and beaming binaries are excluded, however.

General references: Hilditch (2001)

1.7.1.1 Classification by components

The number of possible combinations of components is nearly endless. We provide just a few examples; many others are covered incidentally in I17.

Star-star binary: α Cen AB [321]

Type references: Eggleton & Tokovinin (2008); Raghavan et al. (2010); Duchêne & Kraus (2013)

α **Cen AB** *is sidereal source*
Reason for selection of α Cen AB: Closest example; well-studied; both components in I17
Notes on α Cen AB: Projected separation: 1.7–21.8″; actual semimajor axis: 23.5 AU; part of a hierarchical triple with Proxima Centauri (a_{Proxima} = 8,700 AU), also in the catalog
Works relating α Cen AB to type: Kervella et al. (2016b)
General works about α Cen AB: Kervella et al. (2017)
α Cen AB in I17
Relationships between α Cen AB and other Exotica Catalog objects: Gravitationally bound to: Proxima b [084]

Multiple young stellar object: T Tau [322]

T Tau *is sidereal source*
Reason for selection of T Tau: T Tau N is eponym of T Tau pre-MS stars; well-studied
Notes on T Tau: Hierarchical triple: T Tau N with T Tau Sa & T Tau Sb
Works relating T Tau to type: Duchêne et al. (2002); Ratzka et al. (2009); Schaefer et al. (2020)

Brown dwarf-brown dwarf: Luhman 16 [323]

Luhman 16 *is sidereal source*
Reason for selection of Luhman 16: Nearest example; both components elsewhere in catalog
Notes on Luhman 16: Separation: 1.5″
Works relating Luhman 16 to type: Luhman (2013)
General works about Luhman 16: Burgasser et al. (2013)
Relationships between Luhman 16 and other Exotica Catalog objects: Is the grouping of: Luhman 16A [138], Luhman 16B [137]

White dwarf-white dwarf: WD 0135-052 [324]

WD 0135-052 *is sidereal source*
WD 0135-052 also known as: Lawd 10
Reason for selection of WD 0135-052: Nearby example; known example within 20 pc confirmed with *Gaia* (Toonen et al. 2017); components are relatively close to each other
Notes on WD 0135-052: Orbital period: 1.56 days; separation: 0.027 AU; barycentric orbital velocities: 96 $\mathrm{km\,s^{-1}}$, 87 $\mathrm{km\,s^{-1}}$; component masses: 0.52 $\mathrm{M_\odot}$, 0.47 $\mathrm{M_\odot}$
Works relating WD 0135-052 to type: Saffer et al. (1988); Toonen et al. (2017)
General works about WD 0135-052: Bergeron et al. (1989)

Relationship to SETI: Close double-degenerate binaries can be used to build Dyson gravity engine, high orbital speed can be used to launch craft at speeds comparable to components (Dyson 1963)

Neutron star-planet mass remnant: PSR J1719-1438 [325]

Notes on type: Companion to neutron star is mass of gas giant, likely the ablated remains of a former star or white dwarf
Type references: Bailes et al. (2011)

PSR J1719-1438 *is sidereal source*
Reason for selection of PSR J1719-1438: Most extreme example known
Notes on PSR J1719-1438: $M_2 \sin i = 0.0012\ \mathrm{M_\odot}$; density: $> 23\ \mathrm{g\,cm^{-3}}$
Works relating PSR J1719-1438 to type: Bailes et al. (2011)

Neutron star-white dwarf: PSR J0437-4715 [272]

PSR J0437-4715 *is sidereal source*
Reason for selection of PSR J0437-4715: Nearby example; well-studied; elsewhere in catalog
Notes on PSR J0437-4715: Period: 5.74 days; separation: 0.080 AU; barycentric orbital velocities: 19 $\mathrm{km\,s^{-1}}$ (NS), 130 $\mathrm{km\,s^{-1}}$

(WD); component masses: 1.9 $M_\odot$ (NS), 0.26 $M_\odot$ (WD); primary is nearest millisecond pulsar
General works about PSR J0437-4715: Johnston et al. (1993); Verbiest et al. (2008)

Relationship to SETI: Close double-degenerate binaries can be used to build Dyson gravity engine, high orbital speed can be used to launch craft at speeds comparable to components (Dyson 1963)

Neutron star-neutron star: PSR B1913+16 [326]

Notes on type: Usually only one NS is observed as a pulsar (see binary pulsar)
Type references: Tauris et al. (2017)

PSR B1913+16 *is sidereal source*
PSR B1913+16 also known as: PSR J1915+1606
Reason for selection of PSR B1913+16: First discovered; most cited of known NS-NS binaries listed in Tauris et al. (2017)
Works relating PSR B1913+16 to type: Hulse & Taylor (1975)

Alternative prototype(s): PSR B1534+11: much closer – second most cited; PSR J1518+4904: closer (630 pc) – component orbital velocities slow (< 100 km s^{-1})
Relationship to SETI: Close double-degenerate binaries can be used to build Dyson gravity engine, high orbital speed can be used to launch craft at speeds comparable to components (Dyson 1963)

1.7.1.2 Post-interaction binaries

Post common envelope binary: HW Vir [327]

Type description: Binary system whose components are in very close orbit after experiencing common envelope phase during mass transfer; contain white dwarf or hot subdwarf primary and dwarf companion
Type references: Schreiber & Gänsicke (2003); Rebassa-Mansergas et al. (2007)

HW Vir *is sidereal source*
HW Vir also known as: BD-07° 3477
Reason for selection of HW Vir: Explicit prototype of subtype with hot subdwarf primary that strongly illuminates red dwarf companion; most cited of Schreiber & Gänsicke (2003) after "peculiar" V471 Tau
Notes on HW Vir: Lee et al. (2009) claimed the existence of two substellar companions from eclipse timing variations, but subsequent data contradicted their solution. Horner et al. (2012a) argued the planetary system would be unstable, but Marsh et al. (2014b) disputes such analyses. Beuermann et al. (2012) advanced another planet solution, although it is now in contradiction with the timing data in Baran et al. (2018).
Works where HW Vir referred to as prototype: Heber (2016); Baran et al. (2018)
General works about HW Vir: Wood et al. (1993); Baran et al. (2018)

1.7.1.3 Phenomenological classification

Binary systems classified by how they are detected. We focus here on methods that define a preferred phase, as these might be used for synchronization in SETI (Shostak 2004). A full list would include visual binaries (resolved, both visible), spectroscopic binaries (radial velocity method), astrometric binaries (dark companion's effects on trajectory imaged), and beaming binaries (relativistic effects on photometry due to motion; Zucker et al. 2007; van Kerkwijk et al. 2010) and ellipsoidal binaries (light curve periodicity due to tidal distortion of companions; Morris 1985).

1.7.1.3.1 Ellipsoidal binaries

Heartbeat binary: KOI 54 [328]

Type description: Subclass of ellipsoidal variables; tidally distorted components, where tides during eccentric orbit excite significant sinusoidal pulsations at harmonic of orbital period
Type references: Kumar et al. (1995); Thompson et al. (2012); Pablo et al. (2017)

KOI 54 *is sidereal source*
KOI 54 also known as: HD 187091
Reason for selection of KOI 54: First secure discovery; brightest and most cited example in Thompson et al. (2012)
Notes on KOI 54: Most prominent oscillations at 90th and 91st harmonic of orbital period
Works relating KOI 54 to type: Welsh et al. (2011)

Alternative prototype(s): ι Ori: massive O star binary (Pablo et al. 2017)

1.7.1.3.2 Eclipsing systems

Eclising binary: YY Gem [329]

Type description: Component stars directly occult one another

YY Gem *is sidereal source*
YY Gem also known as: Castor C
Reason for selection of YY Gem: Most cited detached eclipsing binary within 100 pc
Notes on YY Gem: Actual separation: ~ 0.01 AU; both stars chromospherically active; spectral classification: dM1e + dM1e
Works relating YY Gem to type: Torres & Ribas (2002); Butler et al. (2015)
General works about YY Gem: Hussain et al. (2012)
YY Gem in I17
Relationships between YY Gem and objects in I17: Gravitationally bound to: Castor AB

Eclipsing disk: ϵ Aur [330]

Type description: Circumstellar disk (not result of accretion) surrounding secondary eclipses primary
Type references: Rodriguez et al. (2016)

ϵ **Aur** *is sidereal source*
Reason for selection of ϵ *Aur:* First known example; well-studied; disk directly detected with interferometry
Notes on ϵ *Aur:* Period: 27 years; eclipse duration: 18 months; components are F post-AGB star and B5 dwarf with disk
Works relating ϵ *Aur to type:* Hoard et al. (2010); Kloppenborg et al. (2010); Hoard et al. (2012)

Eclipsing binary pulsar: PSR J0737-3039 [331]

Type description: Double pulsar system; one pulsar's magnetosphere eclipses the other neutron star; plasma modulation of radio pulses

PSR J0737-3039 *is sidereal source*
Reason for selection of PSR J0737-3039: Known example; well-studied
Notes on PSR J0737-3039: B's magnetosphere eclipses A
Works relating PSR J0737-3039 to type: Lyne et al. (2004); Kramer & Stairs (2008)
Works about host of PSR J0737-3039: Deller et al. (2009)

1.7.1.3.3 Lensing systems

Self-lensing binary: KIC 8145411 [332]

Type description: Compact remnant gravitationally lenses its companion as it transits, leading to flux increase
Type references: Maeder (1973); Kruse & Agol (2014)

KIC 8145411 *is sidereal source*
Reason for selection of KIC 8145411: Elsewhere in catalog; one of a few known examples
Notes on KIC 8145411: Lens is ELM WD
Works relating KIC 8145411 to type: Masuda et al. (2019)
General works about KIC 8145411: Masuda et al. (2019)

1.7.1.3.4 Other binaries

Detached active binary: RS CVn [333]

Type description: Detected by periodic variations in light curve due to synchronous rotation carrying surface features like sunspots on one star into and out of view; signs of chromospheric activity, not generally induced by companion directly but instead by fast synchronous rotation
Notes on type: Includes RS CVn (giant+late MS/subgiant) and BY Dra (late MS+late MS) binaries

Relationship with other types: Components can include RS CVn flare stars
Type references: Eaton & Hall (1979); Drake et al. (1989); Dempsey et al. (1993)

RS CVn *is sidereal source*
Reason for selection of RS CVn: Eponym of one subclass; explicit prototype
Works where RS CVn referred to as prototype: Rodonò et al. (2001); Xiang et al. (2020)
Works relating RS CVn to type: Rodonò et al. (2001); Xiang et al. (2020)

1.7.2 Star clusters

Non-hierarchical, gravitationally bound groups of stars. The division of clusters into open and globular types may be an artifact of the Milky Way's star formation history (Krumholz et al. 2019).

General references: Kharchenko et al. (2013); Krumholz et al. (2019)

1.7.2.1 Open star clusters

Relatively low mass ($\lesssim 10^4$ $M_\odot$) star clusters generally found in the disks of star-forming galaxies. They tend to be high metallicity and young, although there are exceptions to both criteria. Open clusters have a single stellar population, formed all at the same time.

Abbreviation for general class: OC
General references: Cantat-Gaudin et al. (2018)

Young: IC 2391 [334]

IC 2391 *is sidereal source*
Reason for selection of IC 2391: Well-studied; young; compact on sky
Notes on IC 2391: Age: 50 ± 5 Myr
Works relating IC 2391 to type: Barrado y Navascués et al. (2004); Spezzi et al. (2009)
General works about IC 2391: Barrado y Navascués et al. (2004); Spezzi et al. (2009)

Alternative prototype(s): M45: more famous – covers more of sky, harder to survey

Old: M67 [335]

Notes on type: Janes & Phelps (1994) notes that most open clusters dissolve within hundreds of Myr, and "old" open clusters are those that survive longer; Friel (1995) defines as $\gtrsim 1$ Gyr in age
Type references: Janes & Phelps (1994); Friel (1995)

M67 *is sidereal source*
M67 also known as: NGC 2682
Reason for selection of M67: Well-studied (second most cited open cluster within 3 kpc on Simbad); second most cited of Janes & Phelps (1994) list after the Hyades; age
Notes on M67: Age: 3.5 – 5.4 Gyr
Works relating M67 to type: Davenport & Sandquist (2010); Gonzalez (2016)
General works about M67: Gaia Collaboration et al. (2018a)
Relationships between M67 and other Exotica Catalog objects: Contains within projected sky region: M67-S1063 [685], M67-S1237 [231]

Relationship to SETI: M67 is target in Turnbull & Tarter (2003)

1.7.2.2 Super star clusters

Super star cluster: Westerlund 1 [336]

Abbreviations for type: SSC
Type also known as: Young massive cluster (YMC)
Type description: Massive cluster ($\gtrsim 10^4$–10^5 $M_\odot$) of young stars, typically found in starbursts
Type references: Meurer et al. (1995); Portegies Zwart et al. (2010)

Westerlund 1 *is sidereal source*

Reason for selection of Westerlund 1: Likeliest, most extreme Galactic example
Caveats about selection of Westerlund 1: Distance and mass disputed (Davies & Beasor 2019; Aghakhanloo et al. 2020); depending on mass threshold, no Local Group cluster may qualify as SSC (Hunt & Hirashita 2009)
Notes on Westerlund 1: Mass: $\sim 10^5$ $M_\odot$
Works relating Westerlund 1 to type: Clark et al. (2005); Mengel & Tacconi-Garman (2007)
General works about Westerlund 1: Davies & Beasor (2019); Aghakhanloo et al. (2020)

1.7.2.3 Faint fuzzy

Faint fuzzy: N1023-FF-14 [337]

Type description: Class of diffuse star clusters generally found in galactic disks; effective radii of 10–15 pc; classically are red, and thought to be very large old open clusters or the result of open cluster mergers
Notes on type: Although none are known in the Milky Way, Peng et al. (2006) likens their "diffuse cluster" sample, which overlaps with the faint fuzzies, to old open clusters; Forbes et al. (2014) notes a subclass of blue faint fuzzies, the result of recent star formation; although size is similar to "extended clusters", the latter are related to globular clusters
Type references: Larsen & Brodie (2000); Brodie & Larsen (2002); Peng et al. (2006); Chies-Santos et al. (2013); Forbes et al. (2014)

N1023-FF-14 *is sidereal source*
Reason for selection of N1023-FF-14: Among first discovered; one of most cited in Brodie & Larsen (2002)
Notes on N1023-FF-14: Host is NGC 1023
Works relating N1023-FF-14 to type: Larsen & Brodie (2000); Brodie & Larsen (2002)

1.7.2.4 Globular star clusters

Star clusters generally found in the non-star forming halos and spheroidal components of galaxies, including quiescent galaxies. They tend to be old and low metallicity, but this is not universal. Globular clusters can be massive ($\sim 10^6$ $M_\odot$ or more), but sparse examples are known. Globular clusters have distinctive chemical patterns, including an anticorrelation between sodium and oxygen abundances; they also show evidence of having several populations of stars, formed over a limited interval (Gratton et al. 2012).

Globular cluster systems in galaxies have bimodal color distributions, divided into red, metal-rich globulars and blue, metal-poor globulars (Brodie & Strader 2006). The color division is not commonly used for the Milky Way, but there is a similar division between metal-rich bulge-disk and metal-poor halo clusters, respectively (Brodie & Strader 2006; Forbes & Bridges 2010). Since most of the globulars are selected from the Milky Way, we use the three-way division into bulge-disk, young halo, and old halo populations as described in Mackey & Gilmore (2004) and references therein. Additional subtypes are based on internal structure and luminosity.

General references: Mackey & van den Bergh (2005); Brodie & Strader (2006); Forbes & Bridges (2010); Harris (2010); Gratton et al. (2012)

1.7.2.4.1 Location–age classification

Bulge-disk globular cluster: 47 Tuc [338]

Type description: Relatively metal-rich; concentrated in Galactic plane; old
Type references: Mackey & Gilmore (2004); Mackey & van den Bergh (2005); Forbes & Bridges (2010)

47 Tuc *is sidereal source*
47 Tuc also known as: NGC 104
Reason for selection of 47 Tuc: Very well-studied, most cited globular on Simbad; implicit prototype
Notes on 47 Tuc: Age: 13.06 Gyr; [Fe/H]: -0.78; [Fe/H] has narrow range, supporting single stellar population (Willman & Strader 2012)
Works where 47 Tuc referred to as prototype: Dinescu et al. (1999)
Works relating 47 Tuc to type: Mackey & van den Bergh (2005); Forbes & Bridges (2010)
General works about 47 Tuc: Gilliland et al. (2000); Baumgardt & Hilker (2018)

Young halo globular cluster: M15 [339]

Type description: Generally metal-poor; typically found in distant Galactic halo; likely formed in now-disrupted dwarf

galaxy; younger on average than old halo clusters, but old examples exist
Type references: Mackey & Gilmore (2004); Mackey & van den Bergh (2005); Forbes & Bridges (2010)

M15 *is sidereal source*
M15 also known as: NGC 7078
Reason for selection of M15: Third most cited globular on Simbad; elsewhere in the catalog
Notes on M15: Age: 12.93 Gyr; [Fe/H]: -2.02
Works relating M15 to type: Mackey & van den Bergh (2005); Forbes & Bridges (2010)
General works about M15: Forbes & Bridges (2010); Mackey & van den Bergh (2005); Stetson (1994); Baumgardt & Hilker (2018)

Old halo globular cluster: NGC 6752 [340]

Type description: Generally metal-poor; typically found in near Galactic halo; likely a mixture of former dwarf galaxy and Milky Way globulars; older on average than young halo clusters, but old examples exist
Type references: Mackey & Gilmore (2004); Mackey & van den Bergh (2005); Forbes & Bridges (2010)

NGC 6752 *is sidereal source*
Reason for selection of NGC 6752: Explicit prototype; well-studied (sixth most cited globular on Simbad)
Caveats about selection of NGC 6752: Anomalous kinematics indicated by distribution of pulsars (D'Amico et al. 2002; Ferraro et al. 2003b)
Works where NGC 6752 referred to as prototype: Dinescu et al. (1999)
Works relating NGC 6752 to type: Mackey & van den Bergh (2005); Forbes & Bridges (2010)
General works about NGC 6752: Ferraro et al. (2003b); D'Amico et al. (2002); Baumgardt & Hilker (2018)
Relationships between NGC 6752 and other Exotica Catalog objects: Contains within projected sky region: PSR J1911-5958A [665]

1.7.2.4.2 Internal property classification

Core-cusp globular cluster: M15 [339]

Type description: Power law cusp surface brightness distribution towards center; resulted from gravitational collapse of cluster core
Type references: Stetson (1994)

M15 *is sidereal source*
M15 also known as: NGC 7078
Reason for selection of M15: Well-studied example; third most cited globular on Simbad; elsewhere in the catalog
Works relating M15 to type: Stetson (1994)
General works about M15: Forbes & Bridges (2010); Mackey & van den Bergh (2005); Stetson (1994); Baumgardt & Hilker (2018)

Extended globular cluster: M31-EC4 [341]

Abbreviations for type: ECs
Type description: Globular cluster with abnormally large half-light radii (~ 30 pc) but typical mass; not present in Milky Way
Notes on type: Although size is similar to "faint fuzzies", the latter are related to open clusters
Type references: Huxor et al. (2005); Brodie et al. (2011)

M31-EC4 *is sidereal source*
Reason for selection of M31-EC4: Most cited of the original four discovered in M31
Notes on M31-EC4: Radius: 24 pc (core), 34 pc (half-light)
Works relating M31-EC4 to type: Collins et al. (2009)
Works about host of M31-EC4: McConnachie et al. (2005)
Relationships between M31-EC4 and other Exotica Catalog objects: Adjacent on sky to (sharing parent object with): (GC) 037-B327 [610], M32 [396], G1 [609], NGC 205 [398]
Relationships between M31-EC4 and objects in I17: Gravitationally bound to: M31

Ultrafaint globular cluster: Palomar 1 [342]

Type description: Very faint ($M_V > -3$) low mass ($\lesssim$ 2,000 $M_\odot$) star cluster; size comparable to globular cluster; found in Galactic halo; possible remnant of globular cluster
Type references: Niederste-Ostholt et al. (2010)

Palomar 1 *is sidereal source*
Reason for selection of Palomar 1: Explict prototype; most cited of Niederste-Ostholt et al. (2010)
Notes on Palomar 1: Characteristics unlike Galactic globular and open clusters, probably from dwarf galaxy
Works relating Palomar 1 to type: Niederste-Ostholt et al. (2010)
General works about Palomar 1: Sakari et al. (2011)

1.7.2.5 Nuclear star clusters

Nuclear star cluster: Central Cluster [343]

Abbreviations for type: NSC
Type description: Star cluster presently at the center of a galaxy, around the central black hole if present; long star-formation history, can include both old and young stars; effective radii of a few parsecs
Type references: Ferrarese et al. (2006); Rossa et al. (2006); Seth et al. (2008); Georgiev & Böker (2014)

Central Cluster *is sidereal source*
Reason for selection of Central Cluster: Very well-studied; closest; several members elsewhere in catalog
Notes on Central Cluster: Includes two disks of young stars within 0.5 pc of Sgr A* and power-law density cusp of older stars (possibly with small core)
Works relating Central Cluster to type: Paumard et al. (2006); Hailey et al. (2018); Gravity Collaboration et al. (2019b); Gallego-Cano et al. (2020)
Relationships between Central Cluster and other Exotica Catalog objects: Contains within projected sky region: G2 [669], IRS 16E [604], IRS 16C [668], S0-2 [667], S4711 [574], Sgr A* [471]

Stripped nucleus: ω Cen [344]

Type description: Nuclear star cluster stripped from former host galaxy, now appears like massive globular cluster in galactic halo
Caveats about type: Probably overlaps with ultracompact dwarf galaxies (Brodie et al. 2011)
Type references: Meylan et al. (2001)

ω **Cen** *is sidereal source*
ω Cen also known as: NGC 5139
Reason for selection of ω Cen: Well-studied (second most cited globular on Simbad); nearby
Notes on ω Cen: Has large number of distinct stellar populations with metallicity spread; historically classified as globular cluster
Works relating ω Cen to type: Bekki & Freeman (2003)
General works about ω Cen: Villanova et al. (2007)

1.7.3 Stellar associations

Stellar associations are loosely bound or unbound groups of young stars, formed in the same broad star-formation region. They are classified (in roughly increasing order of luminosity) as T associations for their T Tauri stars, R associations for their reflection nebulae, and OB associations for their bright O and B stars. T associations are quite common, but the prototypical examples, like the Taurus-Auriga association, are too large to observe practically.

R association: CMa R1 [345]

Type description: Assemblage of reflection nebulae tracing site of widespread low–intermediate mass star formation
Type references: Racine (1968)

CMa R1 *is sidereal source*

Reason for selection of CMa R1: One of most compact in Racine (1968)
General works about CMa R1: Gregorio-Hetem et al. (2009)

Alternative prototype(s): Tau R1 (Pleadies; M45)

1.7.3.1 OB associations

Relatively low density assemblages of young, massive stars and their birth star clusters, typically gravitationally unbound. They span entire giant molecular clouds.

General references: Elmegreen & Efremov (1996)

Compact OB association: Cyg OB2 [346]

Type references: de Zeeuw et al. (1999)

Cyg OB2 *is sidereal source*
Reason for selection of Cyg OB2: Well-studied; implicit prototype; compact on sky
Notes on Cyg OB2: Radius: 13′ (half-light), 29′ (core); mass: 30,000 $M_\odot$; central density: 100 pc^{-3} (high for OB2 associations, much lower than clusters of similar mass)
Works where Cyg OB2 referred to as prototype: Massey & Thompson (1991); Knödlseder (2000)
Works relating Cyg OB2 to type: Massey & Thompson (1991); Knödlseder (2000); Wright et al. (2010)
Relationships between Cyg OB2 and other Exotica Catalog objects: Within the sky region occupied by: Cygnus Cocoon [387]; Adjacent on sky to (sharing parent object with): TeV J2032+4130 [738]

Scaled OB association: NGC 604 [347]

Type description: Massive and larger version of OB associations, with similar densities; found in giant HII regions; can be over 100 pc in radius
Type references: Hunter (1999); Maíz-Apellániz (2001)

NGC 604 *is sidereal source*
Reason for selection of NGC 604: Explicit prototype
Works relating NGC 604 to type: Maíz-Apellániz et al. (2004)
General works about NGC 604: Crowther (2019); Tachihara et al. (2018); Maíz-Apellániz et al. (2004); Melnick (1980); Hunter et al. (1996)
Works about host of NGC 604: McConnachie et al. (2005)
Relationships between NGC 604 and objects in I17: Within the sky region occupied by: M33

Jet-induced OB association: Cen A outer filament [348]

Type description: OB associations formed when jet from AGN impacts and squeezes extragalactic gas, triggering star formation

Cen A outer filament *is sidereal source*
Reason for selection of Cen A outer filament: Main known example; host well-studied and elsewhere in ctalog
Works relating Cen A outer filament to type: Blanco et al. (1975); Mould et al. (2000); Fassett & Graham (2000); Rejkuba et al. (2002); Salomé et al. (2016)
Works about host of Cen A outer filament: Tully et al. (2015)
Relationships between Cen A outer filament and other Exotica Catalog objects: Within the sky region occupied by: Centaurus A [479]

1.8 ISM and Nebulae

A phylum covering the gas located within galaxies that is not captured by a stellar objects or planet. They consist of gases and plasmas, with a sprinkling of dust grains. They also are generally not gravitationally self-bound. The three main subcategories are (1) the diffuse interstellar medium (ISM) cospatial with the stellar population, (2) outflows and inflows onto stellar objects (including collapsed stars and interacting binary systems), and (3) the circumgalactic medium in galactic halos, which includes galactic-scale outflows and inflows into the ISM itself. The second group includes many prominent nebulae, including planetary nebulae and supernova remnants.

The interstellar medium (ISM) is very complicated, and has structure on scales ranging from kilometers to entire galaxies. Historically, the ISM has been divided into "phases" with drastically different temperatures and densities but in approximate pressure equilibrium. In the three phase picture, on large scales, there is cold ($\sim$ 10–100 K) atomic and molecular gas, warm ($\sim$ 1,000–10,000 K) atomic and ionized gas, and hot ($\gtrsim 10^5$ K) dilute plasma excavated by feedback. We use this as a rough classification system, but the reality is more complex. On small scales, there are many structures produced by feedback from star formation. In addition, there is a pervading non-thermal ISM, in the form of magnetic fields and cosmic rays (CRs). Finally, gas flows in and out of the galaxy, exchanging with a circumgalactic medium (CGM). The relative importance of these components varies with galaxy type; the great majority of the ISM in elliptical galaxies is hot, while it cold gas dominated in high-redshift star-forming galaxies.

Many of the ISM's structures are too large and too diffuse to observe as "objects". In addition, the ISM has a multi-scale self-similar nature, so the boundaries of "objects" are somewhat arbitrary. This self-similarity arises from turbulence, a ubiquitous phenomenon in the ISM.

General references: Ferrière (2001); Cox (2005); Draine (2011)

1.8.1 Cold ISM

1.8.1.1 Molecular clouds and molecular gas

Molecular gas makes up about one-sixth of the mass of the Milky Way's ISM, although it fills only 0.1% of its volume. It is also the site of star-formation, particularly in dense molecular clouds. Because of the coldness of this gas, turbulence is hypersonic. This results in a fractal hierarchy of structures, with most of the mass concentrated in extremely overdense clumps. On the other hand, most of the volume of the molecular ISM is in the form of the "diffuse" molecular gas – although at ~ 100 cm^{-3}, still about a hundred times denser than the Galactic ISM as a whole.

Molecular clouds are here classed according to column density into translucent and dark clouds, with the dark clouds further divided by scale. Molecular clouds have self-similar structure, and although they are sometimes labeled as complexes, clouds, clumps, and cores in the literature, the divisions are arbitrary (see Wu et al. 2010).

General references: Mac Low & Klessen (2004); Snow & McCall (2006); Carilli & Walter (2013)

1.8.1.1.1 Diffuse molecular clouds

Molecular clouds with relatively little obscuration. The diffuse molecular clouds proper have $A_V \lesssim 1$, and carbon is singly-ionized in them (Snow & McCall 2006).

Translucent sightline: ζ Oph cloud [349]

Type description: Intermediate column density sightline with $1 \lesssim A_V \lesssim 5$ from one or more semi-diffuse molecular cloud; densities $\sim 1{,}000$ cm^{-3}; relatively low amounts of CO, which is used to trace molecular gas, due to photodissociation

Type references: Rachford et al. (2002); Snow & McCall (2006)

ζ **Oph cloud** *is sidereal source*

Reason for selection of ζ Oph cloud: Explicit prototype; well-studied; primary studied sightline already in catalog

Notes on ζ Oph cloud: Angular size of responsible clouds: $\sim 4\,\mathrm{deg} \times 1\,\mathrm{deg}$ (in CO); consists of two overlapping clouds, at different velocities

Works where ζ Oph cloud referred to as prototype: Snow & McCall (2006); Liszt et al. (2009)

Works relating ζ Oph cloud to type: van Dishoeck & Black (1986); Liszt et al. (2009)

Relationships between ζ Oph cloud and other Exotica Catalog objects: Contains within projected sky region: ζ Oph bow shock [363], ζ Oph [240]

Photodissociation region: NGC 7023 [350]

Type description: Low density atomic/molecular region (diffuse cloud or edge of dense molecular cloud) where chemistry is driven by UV radiation

Type references: Hollenbach & Tielens (1999)

NGC 7023 *is sidereal source*

Reason for selection of NGC 7023: Well-studied; elsewhere in catalog

Notes on NGC 7023: Edge of dark cloud; distance usually quoted is that of HD 200775 within the nebula (Benisty et al. 2013)

Works relating NGC 7023 to type: Köhler et al. (2014)
General works about NGC 7023: Sellgren et al. (2007); Köhler et al. (2014)

1.8.1.1.2 Dark molecular clouds

Molecular clouds dense enough to have high levels of dust extinction ($A_V \gtrsim 5$), and the site of most star-formation. These clouds are mapped in CO, which is the main form of carbon. Not to be confused with the "dark molecular gas", which is molecular gas that does not show up in CO maps: dark molecular gas is found where obscuration is weak as in diffuse molecular clouds (Wolfire et al. 2010).

Although these structures are roughly grouped by mass and size scale into complexes, clouds, clumps, and cores, the division between these varies in the literature (Wu et al. 2010).

General references: Bergin & Tafalla (2007); Heyer & Dame (2015)

Giant molecular cloud: Orion A [351]

Type description: High-mass dense aggregates of molecular gas; mass in the range $\gtrsim 10^3$–10^4 M$_\odot$; tens of parsecs wide; may be grouped into even larger complexes; may form into several star clusters
Type references: Dame et al. (2001); Rice et al. (2016)

Orion A *is sidereal source*
Reason for selection of Orion A: Explicit prototype; well-studied
Notes on Orion A: Mass: $\sim 10^5$ M$_\odot$; angular size: ~ 7 deg $\times 1$ deg
Works where Orion A referred to as prototype: Großschedl et al. (2018)
Works relating Orion A to type: Meingast et al. (2016); Großschedl et al. (2018)
General works about Orion A: Megeath et al. (2012)
Relationships between Orion A and other Exotica Catalog objects: Contains within projected sky region: ι Ori AB [192], M42 [357], Orion hot core [355]

Infrared dark cloud: G028.37+00.07 [352]

Type description: Highly obscured ($A_V \gtrsim 20$) smaller cloud; mass: $\sim 10^2$–10^4 M$_\odot$; sites of high-mass star formation, will probably become star clusters
Type references: Rathborne et al. (2016)

G028.37+00.07 *is sidereal source*
Reason for selection of G028.37+00.07: Most cited of Rathborne et al. (2016); well-studied
Works relating G028.37+00.07 to type: Carey et al. (1998); Lin et al. (2017)
General works about G028.37+00.07: Wang et al. (2011)

Dark cloud: TMC-1 [353]

Type description: Obscured cloud of intermediate mass; mass: ~ 10–$1{,}000$ M$_\odot$; sites of low-mass star formation

TMC-1 *is sidereal source*
Reason for selection of TMC-1: Explicit prototype; well-studied
Notes on TMC-1: Also a clump or filament in HCL 2 molecular cloud; angular size: $\sim 5' \times 15'$; contains several cores
Works where TMC-1 referred to as prototype: Fuente et al. (2019)
Works relating TMC-1 to type: Pratap et al. (1997); Nutter et al. (2008); Malinen et al. (2012); Fehér et al. (2016)
General works about TMC-1: Torres et al. (2009)

Starless core: Barnard 68 [354]

Type also known as: Bok globule
Type description: Compact concentration of molecular gas; mass: $\lesssim 100$ M$_\odot$; densities up to 10^6 cm^{-3}; temperatures ~ 10 K; no protostar yet

Barnard 68 *is sidereal source*
Reason for selection of Barnard 68: Explicit prototype; well-studied
Notes on Barnard 68: Recent sources generally cite 125 pc from de Geus et al. (1989)'s distance to the Ophiuchus cloud

Works where Barnard 68 referred to as prototype: Nielbock et al. (2012)
Works relating Barnard 68 to type: Nielbock et al. (2012); Roy et al. (2014)

Hot core: Orion hot core [355]

Type description: Compact concentration of heated molecular gas; heating ascribed to protostar or young star inside it in most cases; mass: 10–1,000 $M_\odot$; densities $\gtrsim 10^6$ cm^{-3}; temperatures $\gtrsim 100$ K; complex chemistry
Type references: van Dishoeck & Blake (1998); Cazaux et al. (2003)

Orion hot core *is sidereal source*
Reason for selection of Orion hot core: Explicit prototype; well studied
Caveats about selection of Orion hot core: Does not contain protostar, unlike usual hot cores
Notes on Orion hot core: Angular size: $15'' \times 15''$
Works where Orion hot core referred to as prototype: van Dishoeck & Blake (1998); Cazaux et al. (2003); Hernández-Hernández et al. (2014)
Works relating Orion hot core to type: Zapata et al. (2011); Wright & Plambeck (2017)
General works about Orion hot core: Kim et al. (2008)
Relationships between Orion hot core and other Exotica Catalog objects: Within the sky region occupied by: Orion A [351], M42 [357]

Alternative prototype(s): IRAS 16293-2422: definitely contains a protostar, elsewhere in catalog (Cazaux et al. 2003) – lower mass

Reflection nebula: NGC 7023 [350]

Type description: Dense cloud illuminated by nearby bright source; dust grains in cloud scatter light, appearing to have a diffuse blue glow
Type references: Magakian (2003)

NGC 7023 *is sidereal source*
Reason for selection of NGC 7023: Well-studied; elsewhere in catalog
General works about NGC 7023: Sellgren et al. (2007); Köhler et al. (2014)

1.8.1.2 Cool atomic gas

Cool HI contains a third of the Galaxy's ISM mass. Despite this, it fills only of order a percent of the Galaxy's volume. The cool HI has been found to contain numerous structures including shells and "filaments". These structures span many degrees on the sky, however, so we decided to include only one extragalactic example in the catalog.

There are also very small ($\sim$ 10–1,000 AU), overpressured Tiny-Scale Atomic Structure (TSAS) clouds. These are not directly observed, but are found through radio HI lines and optical absorption lines on various sightlines.

General references: Heiles (1984); Wolfire et al. (2003); Snow & McCall (2006); Stanimirović & Zweibel (2018)

HI Supershell: Sextans A hole [356]

Type also known as: Supergiant HI shell; kiloparsec-scale HI hole
Type description: Kiloparsec-scale HI shell, requiring $\gtrsim (0.3\text{–}10) \times 10^{53}$ erg to inflate; in dwarf galaxies, can appear like hole in HI; possibly created by star-formation feedback
Type references: Heiles (1979); Walter & Brinks (1999); Kim et al. (1999); Weisz et al. (2009); Warren et al. (2011)

Sextans A hole *is sidereal source*
Reason for selection of Sextans A hole: Small enough angular extent; host in I17
General works about Sextans A hole: van Dyk et al. (1998)
Relationships between Sextans A hole and objects in I17: Within the sky region occupied by: Sextans A

1.8.2 Warm ISM

The warm ISM includes two major subcomponents, the warm neutral medium (WNM) and the warm ionized medium (WIM). These are largely diffuse and thus not practical to study as objects, although of course they will be found along any sightline to distant galactic or extragalactic objects. Tiny structures do exist in the WIM, and they are detected as extreme scattering events. These are transient, however.

General references: Wolfire et al. (2003); Haffner et al. (2009); Stanimirović & Zweibel (2018)

1.8.3 Hot ISM

The hot ISM (HIM) fills about half of the Galaxy's volume, but contains only negligible amounts of gas. It has essentially no discrete structures, although there may be vast bubbles blown by ancient supernovae or star-forming regions. Although we do not include any HIM structures, the Sun is located within one, the Local Bubble.

General references: Sfeir et al. (1999); Mathews & Brighenti (2003)

1.8.4 Emission Nebulae

Relatively small regions, generally overpressured, surrounding an internal power source, where the gas itself glows after being heated.

1.8.4.1 Star-forming HII regions

Emission nebulae surrounding young star clusters and individual OB stars, excavated from star-forming molecular gas.

General references: Habing & Israel (1979); Kurtz (2002)

Classical HII region: M42 [357]

Type description: Parsec-scale nebula

M42 *is sidereal source*

Reason for selection of M42: One of best studied

Works relating M42 to type: O'dell (2001)

General works about M42: O'dell (2001)

Relationships between M42 and other Exotica Catalog objects: Within the sky region occupied by: Orion A [351]; Adjacent on sky to (sharing parent object with): ι Ori AB [192]; Contains within projected sky region: Orion hot core [355]

Ultracompact HII region: W3(OH) [358]

Type description: Entire HII region is small ($\lesssim$ 0.1 pc in radius), dense ($\gtrsim 10^4$ cm^{-3}) surrounding only one or a few OB stars; expanding and overpressured; frequently site of maser emission

Type references: Kurtz (2002); Churchwell (2002)

W3(OH) *is sidereal source*

Reason for selection of W3(OH): Explicit prototype; given example in Habing & Israel (1979); very well studied; elsewhere in catalog

Works where W3(OH) referred to as prototype: Hachisuka et al. (2006)

Works relating W3(OH) to type: Hirsch et al. (2012)

General works about W3(OH): Sullivan (1973); Hachisuka et al. (2006); Elitzur (1992); Hirsch et al. (2012)

Giant HII region: NGC 3603 [359]

Type description: Dilute HII region; tens to hundreds of parsecs wide; surround super star clusters or large OB associations

Type references: Kennicutt (1984); Crowther (2019)

NGC 3603 *is sidereal source*

Reason for selection of NGC 3603: Galactic example; contains one of the brightest Galactic clusters

Caveats about selection of NGC 3603: Kennicutt (1984): extremely diverse class, explicitly has *no* prototype

Works relating NGC 3603 to type: Di Cecco et al. (2015)

General works about NGC 3603: Fukui et al. (2014); Moffat et al. (2002)

Relationships between NGC 3603 and other Exotica Catalog objects: Contains within projected sky region: [SBD2011] 5 [686], HD 97950 [606]

Alternative prototype(s): 30 Dor: prototype "supergiant" HII region, already in Superlatives

1.8.4.2 *Star-formation maser regions*

Dense clouds that emit coherent molecular line radiation at centimeter wavelengths, particularly from OH (at 1.665 and 1.667 GHz) and water (at 22 GHz) but also other molecules (including methanol).

General references: Elitzur (1992)

Maser region: W3(OH) [358]

W3(OH) *is sidereal source*
Reason for selection of W3(OH): Explicit prototype; well-studied; elsewhere in catalog
Notes on W3(OH): OH EIRP: 10^{-5} $L_\odot$; nearby (6″ away) water maser source W3(H2O), H_2O EIRP: 0.003 $L_\odot$
Works where W3(OH) referred to as prototype: Elitzur (1992)
Works relating W3(OH) to type: Sullivan (1973)
General works about W3(OH): Hachisuka et al. (2006); Sullivan (1973); Hirsch et al. (2012)

OH megamaser: Arp 220 [360]

Type description: Bright OH maser region(s) found in starburst galaxies; OH molecules pumped by intense infrared background; OH EIRP: $\gg 1$ $L_\odot$
Type references: Baan (1985, 1989); Lo (2005)

Arp 220 *is sidereal source*
Arp 220 also known as: IC 4553
Reason for selection of Arp 220: First discovered; elsewhere in catalog
General works about Arp 220: Smith et al. (1998); Scoville et al. (2015); Downes & Solomon (1998); Yoast-Hull et al. (2015); Martín et al. (2016); Barcos-Muñoz et al. (2015); Sakamoto et al. (2008); Wilson et al. (2014)

1.8.4.3 *Protostellar outflow*

Herbig-Haro object: HH 1 [361]

Type description: Small emission line nebulae, powered by protostellar outflows shocking ISM; may appear like jets, but often just a collection of objects
Type references: Reipurth & Bally (2001)

HH 1 *is sidereal source*
Reason for selection of HH 1: Explict prototype of subclass; second most cited of Reipurth & Bally (2001); well-studied
Works where HH 1 referred to as prototype: Reipurth & Bally (2001)
Works relating HH 1 to type: Hartigan et al. (2011); Raga et al. (2011)

Extended Green Object: EGO G16.59-0.05 [362]

Abbreviations for type: EGO
Type description: Region of shocked molecular hydrogen, excited by outflows from massive young stars
Notes on type: Emission in 4.5 μm bandpass of *Spitzer*, usually colored green in images; not actually green
Type references: Cyganowski et al. (2008); Chen et al. (2010); De Buizer & Vacca (2010)

EGO G16.59-0.05 *is sidereal source*
Reason for selection of EGO G16.59-0.05: Most cited of Chen et al. (2010); part of Cyganowski et al. (2008) catalog
Works relating EGO G16.59-0.05 to type: Cyganowski et al. (2008); Chen et al. (2010); Towner et al. (2019)
General works about EGO G16.59-0.05: Hung et al. (2019)

1.8.4.4 *Stellar bow shock nebula*

Stellar bow shock nebula: ζ Oph bow shock [363]

Type description: Powered by shock between stellar wind of fast-moving star and ISM
Type references: Kobulnicky et al. (2016)

ζ **Oph bow shock** *is sidereal source*
Reason for selection of ζ Oph bow shock: Explicit prototype, one of first discovered

Works where ζ Oph bow shock referred to as prototype: Kobulnicky et al. (2016)
Works relating ζ Oph bow shock to type: Gull & Sofia (1979); Kobulnicky et al. (2016)
Relationships between ζ Oph bow shock and other Exotica Catalog objects: Within the sky region occupied by: ζ Oph bow shock [363]; Contains within projected sky region: ζ Oph [240]

1.8.4.5 Stellar mass loss nebula

Proto-planetary nebula: Red Rectangle nebula [364]

Type description: Envelope recently ejected from post-AGB star, not yet ionized
Notes on type: Not to be confused with protoplanetary disk; is proto-(planetary nebula), not (protoplanet)ary nebula
Type references: Kwok (1993)

Red Rectangle nebula *is sidereal source*
Red Rectangle nebula also known as: HD 44179
Reason for selection of Red Rectangle nebula: Well-known example; elsewhere in catalog
Works relating Red Rectangle nebula to type: Cohen et al. (2004); Witt et al. (2009)
Relationships between Red Rectangle nebula and other Exotica Catalog objects: Contains within projected sky region: HD 44179 [178]

1.8.4.5.1 Planetary nebula

The ionized ejected envelopes of low-to-intermediate mass stars.
General references: Balick (1987); Balick & Frank (2002); Sahai et al. (2011)

Elliptical planetary nebula: Helix Nebula [365]

Helix Nebula *is sidereal source*
Helix Nebula also known as: NGC 7293
Reason for selection of Helix Nebula: Well-studied (fourth most cited of Balick & Frank 2002); elsewhere in catalog
Caveats about selection of Helix Nebula: Sahai et al. (2011) notes Helix would fit their "spiral" class instead
Notes on Helix Nebula: Classified as elliptical (E) in Gorny et al. (1997)
Works relating Helix Nebula to type: O'Dell et al. (2004); Hora et al. (2006)
Relationships between Helix Nebula and other Exotica Catalog objects: Contains within projected sky region: NGC 7293 central star [077]

Bipolar/multipolar planetary nebula: NGC 6302 [366]

Type description: Morphology is one or more pair of lobes extending from the central star
Type references: Corradi & Schwarz (1995)

NGC 6302 *is sidereal source*
NGC 6302 also known as: Butterfly Nebula
Reason for selection of NGC 6302: Well-studied (fifth most cited of Corradi & Schwarz 1995)
Notes on NGC 6302: Not the same "Butterfly Nebula" as in Corradi & Schwarz (1995)
Works relating NGC 6302 to type: Corradi & Schwarz (1995); Meaburn et al. (2005, 2008)

Binary nucleus planetary nebula: NGC 2346 [367]

Type also known as: Binary central stars of planetary nebulae (bCSPNe) – central stars only
Type description: Planetary nebula with two nuclei (central stars), orbital periods of a few days or less; in particular, though to be result of common envelope episode of stellar binary causing severe mass loss, not the end of life of one component
Type references: Bond & Livio (1990); Jones et al. (2015); Hillwig et al. (2016); Gómez-Muñoz et al. (2019)

NGC 2346 *is sidereal source*
Reason for selection of NGC 2346: One of the first discovered; in Bond & Livio (1990)
Caveats about selection of NGC 2346: Some alternate explanations for binary nuclei PNe exist, although are not favored, according to Gómez-Muñoz et al. (2019)

Works relating NGC 2346 to type: Bond & Livio (1990)
General works about NGC 2346: Brown et al. (2019); Gómez-Muñoz et al. (2019)

1.8.4.5.2 Massive star ejecta

Post-red supergiant shell: IRC +10420 [368]

Type description: Massive shell surrounding yellow hypergiant, ejected during mass loss episodes at end of red supergiant phase and subsequently

IRC +10420 *is sidereal source*
Reason for selection of IRC +10420: Known example; well-studied
Works relating IRC +10420 to type: Tiffany et al. (2010); Shenoy et al. (2016)
General works about IRC +10420: Shenoy et al. (2016)

Blue supergiant hourglass nebula: SBW 1 [369]

Type description: Hourglass-shaped nebula formed by mass loss from blue supergiant, before any luminous blue variable phase; can appear as pair of striking interlinking rings on sky
Type references: Brandner et al. (1997a,b); Smith et al. (2007); Gvaramadze et al. (2015)

SBW 1 *is sidereal source*
Reason for selection of SBW 1: Most similar to SN 1987A progenitor and its ring nebula; less likely to be luminous blue variable
Works relating SBW 1 to type: Smith et al. (2007, 2013)

Alternative prototype(s): Sanduleak -69° 202 nebula (SN 1987A): very famous example – much more distant; Sher 25: possibly first Galactic example – may be LBV

Luminous blue variable shell: Homunculus Nebula [370]

Type description: Massive shell around luminous blue variable, ejected during giant eruptions; contains of order $\gtrsim 1$ $M_\odot$ per eruption
Type references: Nota et al. (1995)

Homunculus Nebula *is sidereal source*
Reason for selection of Homunculus Nebula: Most studied example; around η Car, already in catalog
Notes on Homunculus Nebula: Mass: ~ 10 $M_\odot$
Works relating Homunculus Nebula to type: Morse et al. (1998); Smith et al. (2003); Steffen et al. (2014)
General works about Homunculus Nebula: Smith (2017); Shull & Danforth (2019)
Relationships between Homunculus Nebula and other Exotica Catalog objects: Contains within projected sky region: η Car [203]

Wolf-Rayet bubble: S 308 [371]

Type description: Bubble formed when fast wind of Wolf-Rayet star intercepts previous mass loss and compresses into shell; can have more complicated morphology
Type references: Toalá et al. (2015)

S 308 *is sidereal source*
Reason for selection of S 308: Surrounds HD 50896, elsewhere in catalog; progenitor most cited of Toalá et al. (2015)
Notes on S 308: S 308 and NGC 6888 only known examples detected in X-rays; 40′ diameter
Works relating S 308 to type: Chu et al. (2003); Toalá et al. (2012)
Relationships between S 308 and other Exotica Catalog objects: Contains within projected sky region: EZ CMa [198]

1.8.4.6 Supernova remnants

Supernova remnants includes those from both core collapse and thermonuclear supernovae.

Historically, their morphology was classified as shell, plerion, or composite (plerion inside a shell). Plerions are placed under pulsar wind nebulae. X-ray studies have added another morphological category, the thermal composite SNRs.

Abbreviation for general class: SNR
General references: Vink (2012); Green (2019)

Shell supernova remnant: Cas A [372]

Type description: Most emission appears to come from edges, with dark interior, as shock sweeps up ISM

Cas A *is sidereal source*
Reason for selection of Cas A: Very well-studied; radio calibrator (Baars et al. 1977); neutron star elsewhere in catalog
Works relating Cas A to type: Reed et al. (1995); Hwang & Laming (2012); Milisavljevic & Fesen (2013)

Composite supernova remnant: Kes 75 [373]

Type description: Shell-type supernova remnant with a small pulsar wind nebula (plerion) expanding into its center, possibly shocking interior

Kes 75 *is sidereal source*
Kes 75 also known as: SNR G29.7-0.3
Reason for selection of Kes 75: Explicit prototype; example given in Vink (2012); well-studied
Works where Kes 75 referred to as prototype: Helfand et al. (2003)
Works relating Kes 75 to type: Helfand et al. (2003); Temim et al. (2019)
General works about Kes 75: Verbiest et al. (2012)

Mixed-morphology supernova remnant: W44 [374]

Type also known as: Thermal-composite supernova remnant
Type description: Edges bright and interior dark in radio, but interior glows with thermal X-rays
Type references: Rho & Petre (1998)

W44 *is sidereal source*
W44 also known as: SNR G034.6-00.5
Reason for selection of W44: Explicit prototype; most cited of prototypical-grade examples in Rho & Petre (1998)
Notes on W44: Also contains an old, offset pulsar wind nebula surrounding PSR B1853+01; interacting with molecular cloud
Works where W44 referred to as prototype: Shelton et al. (2004); Castelletti et al. (2007)
Works relating W44 to type: Shelton et al. (2004); Castelletti et al. (2007); Abdo et al. (2010c)
General works about W44: Hoffman et al. (2005); Ranasinghe & Leahy (2018); Goss & Robinson (1968)

Young supernova remnant: SN 1987A [375]

Type description: Shock still expanding into progenitor wind, hasn't reached ambient ISM; shock-dominated (SNR) luminosity, although some radioisotope luminosity (SN) remains

SN 1987A *is sidereal source*
Reason for selection of SN 1987A: Well-studied; youngest known example within Local Group
Caveats about selection of SN 1987A: SN 1987A was very underluminous
Works relating SN 1987A to type: McCray & Fransson (2016)
Works about host of SN 1987A: Pietrzyński et al. (2019)
Relationships between SN 1987A and other Exotica Catalog objects: Contains within projected sky region: NS 1987A [592]; Adjacent on sky to (sharing parent object with): 30 Dor [619], CAL 83 nebula [382], Melnick 34 [600], N159F [385], OGLE LMC-CEP-4506 [702], PSR J0537-6910 [586], R136 a1 [566]
Relationships between SN 1987A and objects in I17: Within the sky region occupied by: LMC

Alternative prototype(s): SN 1978K: long history of monitoring, transitioning to being remnant, extensive interaction with massive wind – was overluminous, much more distant (in NGC 1313) (Kuncarayakti et al. 2016; Ryder et al. 2016)

OH maser supernova remnant: W44 [374]

Type description: Supernova remnant in which shock interacts with molecular cloud; resulting excitation produces OH maser emission at 1.720 GHz

Notes on type: Considerable overlap with the mixed morphology supernova remnants
Type references: Frail et al. (1994, 1996); Wardle & Yusef-Zadeh (2002); Yusef-Zadeh et al. (2003)

W44 *is sidereal source*
W44 also known as: SNR G034.6-00.5
Reason for selection of W44: With W28, one of the original OH maser SNRs in Goss & Robinson (1968)
Works relating W44 to type: Goss & Robinson (1968); Hoffman et al. (2005)
General works about W44: Ranasinghe & Leahy (2018); Abdo et al. (2010c); Shelton et al. (2004); Castelletti et al. (2007)

1.8.4.7 Pulsar wind nebulae

Bubble or region filled with cosmic rays released when a relativistic "wind" of electrons and positrons from a rotationally-powered pulsar interacting with surrounding material and is shocked.

Abbreviation for general class: PWNe
General references: Gaensler & Slane (2006); Kargaltsev & Pavlov (2008); Bamba et al. (2010)

Plerion: Crab Nebula [376]

Type description: PWN where synchrotron glow fills region around young, luminous pulsar (possibly inside a supernova remnant); also Inverse Compton gamma-rays; generally powered by pulsar spindown

Crab Nebula *is sidereal source*
Reason for selection of Crab Nebula: Extremely well studied; calibrator for X-rays and gamma-rays; nearby; pulsar elsewhere in catalog
Notes on Crab Nebula: Has been observed by *AGILE* and *Fermi*-LAT to flare in gamma-rays, possibly caused by PeV electron acceleration events (Tavani et al. 2011; Abdo et al. 2011)
Works relating Crab Nebula to type: Hester (2008); Bühler & Blandford (2014)
General works about Crab Nebula: Wilson-Hodge et al. (2011)
Relationships between Crab Nebula and other Exotica Catalog objects: Contains within projected sky region: Crab pulsar [266]

Magnetar wind nebula: SWIFT J1834.9-0846 nebula [377]

Type description: PWN surrounding magnetar (pulsar with very strong magnetic field $\gtrsim 10^{14}$ G); may be powered by magnetic field decay instead of spindown
Notes on type: Distinct from transient radio nebulae of magnetar (SGR) eruptions (Gaensler et al. 2005; Gelfand et al. 2005)

SWIFT J1834.9-0846 nebula *is sidereal source*
Reason for selection of SWIFT J1834.9-0846 nebula: First confirmed
Notes on SWIFT J1834.9-0846 nebula: Located in supernova remnant W41; $L_X/P_{\mathrm{spin}} \sim 0.1$, much higher than for other PWNe; Torres (2017) suggests that it could be powered by a combination of rotational spindown and external compression
Works relating SWIFT J1834.9-0846 nebula to type: Younes et al. (2016); Granot et al. (2017); Torres (2017)

Alternative prototype(s): Kes 75: possibly contains magnetar

Bow shock pulsar wind nebula: PSR B1957+20 bow shock [378]

Type description: Pulsar wind nebula, powered by shock where the wind of a high-velocity pulsar rams into the ISM
Type references: Kargaltsev et al. (2017)

PSR B1957+20 bow shock *is sidereal source*
Reason for selection of PSR B1957+20 bow shock: Already in catalog; first discovered; pulsar well-studied
Notes on PSR B1957+20 bow shock: Emission in Hα and X-rays
Works relating PSR B1957+20 bow shock to type: Stappers et al. (2003)
Works about host of PSR B1957+20 bow shock: Huang et al. (2012)
Relationships between PSR B1957+20 bow shock and other Exotica Catalog objects: Contains within projected sky region: PSR B1957+20 [319]

TeV halo: Geminga halo [379]

Type description: Large diffuse region of high-energy cosmic ray electrons and positrons surrounding pulsar; very slowly

diffusing (nearly confined) away
Notes on type: Possibly origin of cosmic ray electron and positron excess at TeV energies (Hooper et al. 2017; Profumo et al. 2018)

Geminga halo *is sidereal source*
Reason for selection of Geminga halo: One of two known examples; pulsar already in pulsar
Notes on Geminga halo: TeV emission has FWHM ~ 2.6 deg
Works relating Geminga halo to type: Yüksel et al. (2009); Abeysekara et al. (2017)
General works about Geminga halo: Abdo et al. (2009b)
Works about host of Geminga halo: Faherty et al. (2007)
Relationships between Geminga halo and other Exotica Catalog objects: Contains within projected sky region: Geminga [265]

1.8.4.8 Interacting binary star nebulae

May also include some planetary nebulae that are the ejecta of a common envelope event.

Symbiotic nebula: R Aqr nebula [380]

Type description: Emission nebula around symbiotic binary; gas is mass loss from cool giant, ionization from hot component
Type references: Corradi et al. (1999, 2003)

R Aqr nebula *is sidereal source*
Reason for selection of R Aqr nebula: Well-studied binary (second most cited of Corradi et al. 1999; has own section in Corradi et al. 2003); nearby
Notes on R Aqr nebula: Bipolar shape with torus and jet; D-type symbiotic system
Works relating R Aqr nebula to type: Corradi et al. (2003); Liimets et al. (2018)
Relationships between R Aqr nebula and other Exotica Catalog objects: Contains within projected sky region: R Aqr [281]

Nova remnant: GK Per shell [381]

Type description: Shell around cataclysmic variable, released during a previous nova
Type references: Slavin et al. (1995); Downes & Duerbeck (2000); Darnley et al. (2019)

GK Per shell *is sidereal source*
GK Per shell also known as: Nova Persei 1901
Reason for selection of GK Per shell: Well-studied (second most cited of Slavin et al. 1995 after DQ Her); bright
Notes on GK Per shell: Similar to supernova remnant
Works relating GK Per shell to type: Anupama & Kantharia (2005); Shara et al. (2012); Liimets et al. (2012); Takei et al. (2015)
Relationships between GK Per shell and other Exotica Catalog objects: Contains within projected sky region: GK Per [287]

Supersoft X-ray source nebula: CAL 83 nebula [382]

Type description: Emission nebula; ISM material surrounding supersoft X-ray source ionized by it
Type references: Rappaport et al. (1994); Remillard et al. (1995); Woods & Gilfanov (2016)

CAL 83 nebula *is sidereal source*
Reason for selection of CAL 83 nebula: Known example; central source well-studied and a (distant) prototype of SSSs
Works relating CAL 83 nebula to type: Gruyters et al. (2012); Woods & Gilfanov (2016)
Works about host of CAL 83 nebula: Pietrzyński et al. (2019)
Relationships between CAL 83 nebula and other Exotica Catalog objects: Adjacent on sky to (sharing parent object with): 30 Dor [619], Melnick 34 [600], N159F [385], NS 1987A [592], OGLE LMC-CEP-4506 [702], PSR J0537-6910 [586], R136 a1 [566], SN 1987A [375]
Relationships between CAL 83 nebula and objects in I17: Within the sky region occupied by: LMC

1.8.4.8.1 X-ray binary nebulae

X-ray binary bow shock nebula: SAX J1712.6-3739 nebula [383]

Type description: Bow shock emission nebula surrounding high-velocity X-ray binary

SAX J1712.6-3739 nebula *is sidereal source*
Reason for selection of SAX J1712.6-3739 nebula: Known Galactic example
Notes on SAX J1712.6-3739 nebula: Host is low-mass X-ray binary
Works relating SAX J1712.6-3739 nebula to type: Wiersema et al. (2009)

X-ray binary bubble: Cygnus X-1 shell [384]

Type description: Bubble inflated by jet from X-ray binary
Type references: Russell et al. (2006)

Cygnus X-1 shell *is sidereal source*
Reason for selection of Cygnus X-1 shell: Well-studied; host elsewhere in catalog
Notes on Cygnus X-1 shell: Detected in radio and optical; single-lobe morphology
Works relating Cygnus X-1 shell to type: Gallo et al. (2005); Sell et al. (2015)
Relationships between Cygnus X-1 shell and other Exotica Catalog objects: Contains within projected sky region: Cyg X-1 [273]

Alternative prototype(s): Circinus X-1 bubbles: complex bipolar morphology – may be related to surrounding supernova remnant (Sell et al. 2010; Heinz et al. 2013)

X-ray ionized X-ray binary nebula: N159F [385]

Type description: Nebula around X-ray binary heated and ionized by X-ray emission rather than inflated by jets

N159F *is sidereal source*
Reason for selection of N159F: Known example
Notes on N159F: Ionization source determined from helium line diagnostics
Works relating N159F to type: Pakull & Angebault (1986); Cooke et al. (2008)
Works about host of N159F: Pietrzyński et al. (2019)
Relationships between N159F and other Exotica Catalog objects: Adjacent on sky to (sharing parent object with): 30 Dor [619], CAL 83 nebula [382], Melnick 34 [600], NS 1987A [592], OGLE LMC-CEP-4506 [702], R136 a1 [566], SN 1987A [375]
Relationships between N159F and objects in I17: Within the sky region occupied by: LMC

Ultraluminous X-ray source nebula: W50 [386]

Abbreviations for type: ULXNe
Type description: Large nebula surrounding ULX or supercritical X-ray binary; may be radio nebula or shock- or photo-ionized optical nebula
Type references: Pakull & Mirioni (2003); Abolmasov et al. (2007); Lang et al. (2007); Kaaret et al. (2017)

W50 *is sidereal source*
Reason for selection of W50: Proposed explicit prototype; closest likely example (similar to extragalactic ULX nebulae); well-studied; host (SS 433) elsewhere in catalog
Works where W50 referred to as prototype: Abolmasov (2011)
Works relating W50 to type: Dubner et al. (1998); Lockman et al. (2007); Abolmasov (2011)
General works about W50: Lockman et al. (2007); Begelman et al. (2006a)
Works about host of W50: Marshall et al. (2013)
Relationships between W50 and other Exotica Catalog objects: Contains within projected sky region: SS433 [309]

1.8.5 Nonthermal bubbles

Cosmic ray cocoon: Cygnus Cocoon [387]

Type description: Region filled with high cosmic ray density; CRs accelerated by star-formation activity within

Cygnus Cocoon *is sidereal source*
Reason for selection of Cygnus Cocoon: Known example

Notes on Cygnus Cocoon: Envelopes Cyg OB2; once the most cited unidentified TeV source in Aharonian et al. (2008)
Works relating Cygnus Cocoon to type: Ackermann et al. (2011); Bartoli et al. (2014)
Relationships between Cygnus Cocoon and other Exotica Catalog objects: Contains within projected sky region: Cyg OB2 [346], TeV J2032+4130 [738]

1.8.6 Circumgalactic medium

The circumgalactic medium is a halo extending tens of kiloparsecs surrouding galaxies, and exchanging matter with it. Galactic winds and fountains (in which gas rises and falls out of a disk plane) are two important exchange mechanisms. The CGM is multiphase, like the ISM, with cool, dense clumps, warm gas clouds, and rarefied hot gas forming a galactic corona (e.g., Kacprzak et al. 2008; Stern et al. 2016). Lyman limit systems and Damped Lyman Absorbers (DLAs) detected as absorption lines in the spectra bright background objects trace the CGM of galaxies near the sightline; they are, however, so ubiquitous that we did not include them.

Galactic CGM structures cover large regions on the sky. The two entries listed here are discrete enough to qualify for the catalog.

General references: Katz et al. (1996); Churchill et al. (2000); Chen et al. (2001); Veilleux et al. (2005); Prochaska et al. (2011); Putman et al. (2012); Tumlinson et al. (2017)

Compact high velocity cloud: HVC 125+41-208 [388]

Type description: Neutral cloud at mid–high Galactic latitude, less than about a degree in radius; likely in nearby Galactic halo (a few kiloparsecs away
Type references: Braun & Burton (1999); Putman et al. (2012)

HVC 125+41-208 *is sidereal source*
Reason for selection of HVC 125+41-208: Explicit prototype for subclass of head-tail morphology; well-studied; in Braun & Burton (1999) original catalog
Works where HVC 125+41-208 referred to as prototype: Faridani et al. (2014)
Works relating HVC 125+41-208 to type: Brüns et al. (2001); Davies et al. (2002); Faridani et al. (2014)

Lyman α blob: SSA22a-LAB01 [389]

Type description: Huge Lyman α nebula found at $z \gtrsim 2$; can be over 100 kpc wide; neutral gas cloud surrounding UV-emitting galaxy or AGN, or intergalactic medium cooling and accreting onto galaxies
Type references: Nilsson et al. (2006); Geach et al. (2009); Hine et al. (2016)

SSA22a-LAB01 *is sidereal source*
Reason for selection of SSA22a-LAB01: Well-studied; one of first recognized
Works relating SSA22a-LAB01 to type: Steidel et al. (2000); Beck et al. (2016); Geach et al. (2016); Hine et al. (2016)
Relationships between SSA22a-LAB01 and other Exotica Catalog objects: Within the sky region occupied by: SSA22 [510]

1.9 Galaxies

This phylum covers gravitationally bound, virialized objects that are dominated by dark matter (or non-Newtonian gravity). Their other primary constituents are stars, gas, and in many cases a central black hole (see the Active galactic nuclei phylum for structures involving the latter). In archetypal galaxies like the Milky Way, stars are present by the millions or more, although many small galaxies have merely thousands of stars. Some may be “dark”, lacking any stars at all.

The phylum’s boundaries are not perfectly clear. The largest star clusters and ultracompact dwarf galaxies overlap in size, with some being very large star clusters and others being tidally stripped galaxies. On the other end, galaxy clusters and fossil groups fit the above definition, but are placed under the Galaxy associations phylum by convention. See Willman & Strader (2012) for discussion of these issues.

On the broadest level, we regard the most fundamental distinction between galaxies as being based on star-formation rate and stellar mass. There is a natural division of galaxies in this parameter plane that is robust out to high redshift. The abundance of phenomena that might affect galactic habitability or might be used for astroengineering, like core collapse supernovae, is directly tied to specific star-formation rate. Our primary division is into the quiescents (red sequence), Green Valley galaxies, main-sequence star-forming galaxies (blue cloud), and starbursts. At low redshift, quiescent galaxies are associated with early-type morphologies (ellipticals, spheroidals, and lenticulars), while main sequence galaxies are associated with late-type morphologies (late-type spirals and irregulars), but the correlation is not exact and we specifically include outliers as subtypes. At $z \sim 0$, there is also a correlation with environment, with quiescent galaxies more often located in clusters, although we again include outliers.

To these basic classes, we add a few other classification schemes, based on surface brightness, interaction with neighbors, pure morphological features, and environment.

Abbreviations for frequently consulted references: RC3: de Vaucouleurs et al. (1991); M12: McConnachie (2012); K13: Karachentsev et al. (2013); C14: Comerón et al. (2014); A15: Ann et al. (2015); B15: Buta et al. (2015)

1.9.1 Quiescent (red) galaxies

Galaxies with negligible star-formation rates and typically red colors. In the present Universe, they tend to be found in denser environments, particularly galaxy clusters. Morphologically, they usually are elliptical or lenticular at present. Most stars at present are in quiescent galaxies.

Relationship to SETI: These galaxies lack many phenomena that may pose a hazard to complex life, including core-collapse supernovae, magnetar flares, high-mass X-ray binaries, and long-soft gamma-ray bursts. Some potential hazards remain: short-hard gamma-ray bursts, thermonuclear supernovae, cataclysmic variables, and low-mass X-ray binaries. They also have more rarefied ISMs, which may ease interstellar travel.

1.9.1.1 Large ellipticals

There appears to be a robust division of most large ellipticals into two types: boxy/cored and disky/coreless. The division is based on surface brightness profiles, shape, and X-ray emission. There is also some (though not perfect) correlation with rotation. Massive slow rotators have the more boxy isophotes, brighter X-ray emission, and central light deficits of the boxy/cored ellipticals and the disky/coreless properties correlated with the fast rotators (Emsellem et al. 2007, 2011; Sarzi et al. 2013). The prototypes for the boxy/cored and disky/coreless galaxies were chosen to be unambiguous slow and fast rotators according to Emsellem et al. (2011).

General references: Bender et al. (1989); Kormendy & Bender (1996); Trujillo et al. (2004); Emsellem et al. (2007); Kormendy et al. (2009); Emsellem et al. (2011); Sarzi et al. (2013)

cD galaxies: NGC 6166 [390]

Type also known as: Supergiant ellipticals

Type description: Huge ($\gtrsim$ 100 kpc) elliptical galaxy found in center of galaxy cluster; have a vast envelope of stars, probably from tidally shredded stars

Type references: Dressler (1979, 1984); Bender et al. (2015)

NGC 6166 *is sidereal source*

Reason for selection of NGC 6166: Explicit prototype; part of original Matthews et al. (1964) study; unambiguously brightest cluster galaxy

Works where NGC 6166 referred to as prototype: Morgan & Lesh (1965); Bertola et al. (1986); Bender et al. (2015)

Works relating NGC 6166 to type: Morgan & Lesh (1965); Bender et al. (2015)

General works about NGC 6166: Bertola et al. (1986)

Alternative prototype(s): M87: most famous, closest – peculiar cD galaxy, not brightest cluster galaxy; NGC 4874 or NGC 4889: closer than NGC 6166, in Coma, well-studied

Boxy/cored ellipticals: NGC 4636 [391]

Type description: Ellipticals with rectangular-shaped isophotes; surface brightness flattens somewhat towards center (ignoring nuclei), giving a central light "deficit"; generally giant ellipticals; have X-ray bright hot ISM and more likely to have radio-loud AGN; subset of slow-rotating ellipticals

Type references: Bender et al. (1989); Trujillo et al. (2004); Kormendy et al. (2009); Emsellem et al. (2011)

NGC 4636 *is sidereal source*

Reason for selection of NGC 4636: Definitely cored; usually classed as elliptical instead of lenticular (RC3, A15, B15); well-studied; slow-rotator as determined at both R_e and $R_e/2$ (Emsellem et al. 2011)

Notes on NGC 4636: Fourteenth most cited elliptical/S0 within 30 Mpc in Simbad

Works relating NGC 4636 to type: Kormendy et al. (2009); Emsellem et al. (2011)
Relationships between NGC 4636 and other Exotica Catalog objects: Within the sky region occupied by: Virgo Cluster [506]

Disky/coreless ellipticals: M59 [392]

Type description: Ellipticals with circular isophotes; flattened; surface brightness increases in power law cusp into nucleus; generally medium-sized; lack hot ISM; can be slow or fast rotators
Caveats about type: Emsellem et al. (2011) argues these actually are lenticular galaxies
Type references: Bender et al. (1989); Kormendy et al. (2009); Emsellem et al. (2011)

M59 *is sidereal source*
M59 also known as: NGC 4621
Reason for selection of M59: Definitely cusped profile; classed as elliptiical by RC3, A15; brightest example in Virgo Cluster; well-studied; fast-rotator as determined at both R_e and $R_e/2$ (Emsellem et al. 2011); in I17
Notes on M59: Twenty-sixth most cited elliptical/S0 within 30 Mpc in Simbad
Works relating M59 to type: Kormendy et al. (2009); Emsellem et al. (2011)
M59 in I17
Relationships between M59 and other Exotica Catalog objects: Gravitationally bound to: M59-UCD3 [626]; Within the sky region occupied by: Virgo Cluster [506]

Field elliptical galaxy: NGC 821 [393]

Type description: Elliptical in low-density environment
Type references: Smith et al. (2004); Reda et al. (2004); Stocke et al. (2004)

NGC 821 *is sidereal source*
Reason for selection of NGC 821: Well-studied (second most cited of Smith et al. 2004 and Reda et al. 2004; most cited of Stocke et al. 2004); nearby
General works about NGC 821: Proctor et al. (2005)
NGC 821 in I17

1.9.1.2 Quiescent disks

Lenticular galaxy: NGC 3115 [394]

Type also known as: S0
Type description: Disk galaxies lacking spiral arms; generally red and lacking star-formation; frequently seen as transitional between elliptical and spirals, but also proposed to be separate sequence; may overlap with disky or late-type ellipticals
Type references: van den Bergh (1976, 2009); Emsellem et al. (2011); Kormendy & Bender (2012)

NGC 3115 *is sidereal source*
Reason for selection of NGC 3115: Nearest large example that is not peculiar; classified as lenticular by RC3, K13, B15
Caveats about selection of NGC 3115: B15 classifies it as elliptical
Notes on NGC 3115: Seventeenth most cited elliptical/S0 within 30 Mpc in Simbad

Alternative prototype(s): NGC 5128: nearer – classification disputed, star-forming, AGN; NGC 404: nearer – has star formation

Passive spiral: NGC 4260 [395]

Type description: Spiral galaxy with discernable arms, but lacking star-formation; fairly rare
Type references: Yamauchi & Goto (2004); Moran et al. (2006); Masters et al. (2010)

NGC 4260 *is sidereal source*
Reason for selection of NGC 4260: Spectroscopically identified as quiescent; most cited of Fraser-McKelvie et al. (2016); spiral arms stood out by eye; no reported star formation (Boselli et al. 2015)
Works relating NGC 4260 to type: Fraser-McKelvie et al. (2016, 2018)
General works about NGC 4260: Boselli et al. (2015)

1.9.1.3 *Compact early-type galaxies*

Small early-type galaxies tend to be divided into high-density compact galaxies and low-density dwarf galaxies. There is a vigorous debate about which are more likely to be the analogs of large ellipticals, and which form a separate sequence (for compacts as small "true" ellipticals, Wirth & Gallagher 1984; Kormendy 1985; Bender et al. 1992; Kormendy & Bender 2012; for dwarfs as small "true" ellipticals, Faber 1973; Graham & Guzmán 2003; Chilingarian & Zolotukhin 2015).

Compact early-type galaxies are the small but high surface brightness early-type galaxies.

Compact elliptical galaxy: M32 [396]

Type description: Small ($\sim$ 100–1,000 pc) high-surface brightness galaxies; possibly tidally stripped remnants of bigger galaxies

Type references: Faber (1973); Bekki et al. (2001); Huxor et al. (2011); Paudel et al. (2014); Chilingarian & Zolotukhin (2015); Janz et al. (2016)

M32 *is sidereal source*

Reason for selection of M32: Explicit prototype; only example in Local Group; best studied

Works where M32 referred to as prototype: Faber (1973); Bender et al. (1992); Graham (2002); Huxor et al. (2013); Norris et al. (2014)

Works relating M32 to type: Graham (2002)

General works about M32: McConnachie (2012)

Works about host of M32: McConnachie et al. (2005)

Relationships between M32 and other Exotica Catalog objects: Adjacent on sky to (sharing parent object with): (GC) 037-B327 [610], M31-EC4 [341], G1 [609], NGC 205 [398]

Relationships between M32 and objects in I17: Gravitationally bound to: M31

Ultracompact dwarf galaxy: NGC 4546 UCD-1 [397]

Abbreviations for type: UCD

Type description: Very small ($\lesssim$ 100 pc); intermediate properties between globular clusters and cE galaxies; stellar masses of 10^6–10^8 $M_\odot$; probably tidally-stripped nuclei from dwarf galaxies

Notes on type: Some UCDs are actually very big globular clusters

Type references: Phillipps et al. (2001); Drinkwater et al. (2003); Brodie et al. (2011); Sandoval et al. (2015); Janz et al. (2016)

NGC 4546 UCD-1 *is sidereal source*

Reason for selection of NGC 4546 UCD-1: Extended star-formation history implies likely true galaxy and not globular cluster

Works relating NGC 4546 UCD-1 to type: Norris & Kannappan (2011); Norris et al. (2015)

General works about NGC 4546 UCD-1: Norris et al. (2015)

1.9.1.4 *Dwarf quiescents*

Small quiescent galaxies with low surface brightness. The division between dwarf ellipticals, dwarf spheroidals, and ultra-faint dwarfs is based on luminosity but the labels are arbitrary; we include them to cover a fuller range of galaxy properties.

General references: Ferguson & Binggeli (1994)

Dwarf elliptical: NGC 205 [398]

Abbreviations for type: dE

Type description: Bright dwarf quiescent galaxy; in this work, $M_\star \gtrsim 10^8$ $M_\odot$

NGC 205 *is sidereal source*

NGC 205 also known as: M110

Reason for selection of NGC 205: Brightest in Local Group; well-studied (most citations in Ferguson & Binggeli (1994) review); usually classed as dE (K13

Caveats about selection of NGC 205: Peculiar: has dust near core, star-formation (Hodge 1973)

Notes on NGC 205: M_V: -16.5; M31 satellite

General works about NGC 205: McConnachie et al. (2005); McConnachie (2012)

Relationships between NGC 205 and other Exotica Catalog objects: Adjacent on sky to (sharing parent object with): (GC) 037-B327 [610], M31-EC4 [341], M32 [396], G1 [609]
Relationships between NGC 205 and objects in I17: Gravitationally bound to: M31

Alternative prototype(s): NGC 185: second biggest in Local Group – also has star formation (Martínez-Delgado et al. 1999), classed as dSph in I17; NGC 147: third biggest in Local Group, no star formation – classed as dSph in K13 and I17

Dwarf spheroidal: Sculptor dSph [399]

Abbreviations for type: dSph
Type description: Faint dwarf quiescent galaxy; $L \gtrsim 10^5$ $L_\odot$ in Simon (2019); effective radii of $\sim$ 200–2,000 pc

Sculptor dSph *is sidereal source*
Reason for selection of Sculptor dSph: Explict prototype; first discovered; M_V middle of range between UFDs and NGC 205; in I17
Notes on Sculptor dSph: M_V: -11; Milky Way satellite
Works relating Sculptor dSph to type: Simon (2019)
General works about Sculptor dSph: McConnachie (2012)
Sculptor dSph in I17

Ultrafaint dwarf: UMa II [400]

Abbreviations for type: UFD
Type description: Extremely faint dwarf quiescent galaxy; $L \lesssim 10^5$ $L_\odot$ in Simon (2019); effective radii of $\sim$ 10–100 pc
Type references: Geha et al. (2009); Simon (2019)

UMa II *is sidereal source*
Reason for selection of UMa II: Well-studied (second most cited of confirmed UFDs in Simon (2019)); M_V in middle of range of known UFDs
Notes on UMa II: M_V: -4.2
General works about UMa II: Martin et al. (2008)

Dwarf S0: NGC 4431 [401]

Abbreviations for type: dS0
Type description: Dwarf quiescent with signs of bulge or disk in surface brightness profile; some have spiral or bar morphology; found in galaxy clusters
Type references: Aguerri et al. (2005); Jerjen et al. (2000); Barazza et al. (2002); Graham et al. (2003); Lisker et al. (2006b)

NGC 4431 *is sidereal source*
Reason for selection of NGC 4431: One of original dS0s in Binggeli & Cameron (1991)
Notes on NGC 4431: Has a bar and possibly spiral structure; Barazza et al. (2002) classes as “dSB0/a”
Works relating NGC 4431 to type: Barazza et al. (2002)
Relationships between NGC 4431 and other Exotica Catalog objects: Within the sky region occupied by: Virgo Cluster [506]

1.9.1.5 High redshift quiescent galaxies and analogs

Relic red nugget: NGC 1277 [402]

Type also known as: Massive relic galaxies
Type description: Large mass ($\sim 10^{11}$ $M_\odot$) but small radius ($r_h \sim 1$ kpc); resemble high-z red nuggets; high velocity dispersion, fast rotation, disky; anomalous surface brightness profile
Type references: van den Bosch et al. (2012); Trujillo et al. (2012, 2014); Yıldırım et al. (2015); Ferré-Mateu et al. (2017)

NGC 1277 *is sidereal source*
Reason for selection of NGC 1277: First identified; relatively well studied (though mainly due to claims of overmassive black hole in center)
Works relating NGC 1277 to type: Trujillo et al. (2014)
General works about NGC 1277: van den Bosch et al. (2012)
Relationships between NGC 1277 and other Exotica Catalog objects: Contains within projected sky region: NGC 1277* [689];

Within the sky region occupied by: Perseus Cluster [508]; Adjacent on sky to (sharing parent object with): NGC 1265 [481], NGC 1275 minihalo [513]

Red nugget: MRG-M0150 [403]

Type also known as: Compact early-type galaxy

Type description: Found at $z \sim 2$, apparently hidden at present; large mass ($\sim 10^{11}$ $M_\odot$) but small radius ($r_h \sim 2$ kpc); disk morphologies

Type references: Trujillo et al. (2007); van der Wel et al. (2011); Quilis & Trujillo (2013)

MRG-M0150 *is sidereal source*

Reason for selection of MRG-M0150: Lensed example

Notes on MRG-M0150: Redshift: 2.6; magnification: ~ 11; stellar mass: 3×10^{11} $M_\odot$; effective radius: 1.8 kpc

Works relating MRG-M0150 to type: Newman et al. (2015, 2018)

Large high-redshift quiescent galaxy: MRG-M0138 [404]

Type description: Size similar to present-day ellipticals

MRG-M0138 *is sidereal source*

Reason for selection of MRG-M0138: Lensed example

Notes on MRG-M0138: Redshift: 1.9; magnification: ~ 30; stellar mass: 5×10^{11} $M_\odot$; effective radius: ~ 5–7 kpc

Works relating MRG-M0138 to type: Newman et al. (2018)

1.9.2 Green Valley galaxies

Galaxies lying between red quiescent sequence and blue star-forming cloud on color-magnitude and color-color diagrams, forming stars but at a rate that is slow for their mass. Green Valley galaxies have diverse evolution, with at least three pathways: 1.) former star-forming galaxies whose star-formation was suddenly stopped by a large event; 2.) massive star-forming galaxies (generally early-type spirals) gently slowing down star-formation; and 3.) quiescent galaxies that are "rejuvenated" and start forming stars at a slow rate.

The Milky Way lies in the Green Valley (Mutch et al. 2011; Licquia et al. 2015).

General references: Wyder et al. (2007); Thilker et al. (2010); Salim (2014); Schawinski et al. (2014); Bremer et al. (2018)

1.9.2.1 Green quenching galaxies

Post-starburst galaxy: IC 976 [405]

Abbreviations for type: E+A; K+A

Type description: Otherwise quiescent galaxy with blue component in spectrum; starlight from A dwarfs and K giants, less than 1 Gyr old; star formation has completely ended

Type references: Zabludoff et al. (1996); Dressler et al. (1999); Blake et al. (2004)

IC 976 *is sidereal source*

Reason for selection of IC 976: Relatively well-studied (most cited of Blake et al. 2004); relatively nearby (second nearest of Blake et al. 2004)

1.9.2.2 Green early-type galaxies

Extended star-formation galaxy: NGC 404 [406]

Type description: Early-type galaxy with long tail of star formation extending to present, long after most mass has formed

Type references: Bresolin (2013)

NGC 404 *is sidereal source*

Reason for selection of NGC 404: Nearby example

Caveats about selection of NGC 404: Thilker et al. (2010) proposes instead NGC 404 is rejuvenated galaxy, where star formation had stopped but restarted with influx of gas

Works relating NGC 404 to type: Bresolin (2013)

General works about NGC 404: Thilker et al. (2010)

1.9.2.3 Green spiral galaxies

For reasons discussed in the main spiral galaxy section of the Blue galaxies, we use a relatively coarse classification for spiral galaxies (Section 1.9.3.2). See that section for further details of spiral galaxy classification. Spiral galaxies that are massive and relatively early-type, with large bulges, generally fall into the Green Valley.

Sa-ab spiral galaxy: M81 [407]

Type description: Spiral galaxy with large bulges; generally reddest of spiral galaxies

M81 *is sidereal source*
M81 also known as: NGC 3031
Reason for selection of M81: Nearest example; extremely well studied; strikingly large, bright bulge; in I17
Caveats about selection of M81: Colors typical of red quiescent galaxy
Notes on M81: Morphological type: SA(s)ab (RC3), Sb (K13), SAab (A15), SA(r,rs,nb)a (B15)
General works about M81: Williams et al. (2009)
M81 in I17

Sb-Sbc spiral galaxy: M100 [408]

Type description: Spiral galaxy with medium bulges; generally somewhat bluer than Sa galaxies

M100 *is sidereal source*
M100 also known as: NGC 4321
Reason for selection of M100: Consistent classification; well-studied
Notes on M100: Morphological type: Sbc (RC3), SAB(s)bc (A15), SAB(rs,nr,nb)bc (B15); in Virgo Cluster

Alternative prototype(s): Milky Way: closest example – too large on sky, dust obscured; M31: nearby example, subject of Breakthrough Listen campaign – large on sky

Dwarf Sa-Sb spiral galaxy: D563-4 [409]

Type description: Dwarf galaxy with distinct bulge and some spiral structure; rare; found in field
Type references: Schombert et al. (1995)

D563-4 *is sidereal source*
Reason for selection of D563-4: Most pronounced grand-design-like spiral structure; brightest
Caveats about selection of D563-4: Luminosity marginally small enough to be dwarf ($M_V = -17$); spiral pattern not very obvious on SDSS or Pan-STARRS1 images
Works relating D563-4 to type: Schombert et al. (1995)

Edge-on Sb-Sbc spiral: NGC 891 [410]

Notes on type: Observed properties of spiral galaxies depend on inclination, especially when edge-on
Relationship with other types: Sa-Sb spiral viewed edge-on
Type references: Heidmann et al. (1972); Graham & Worley (2008)

NGC 891 *is sidereal source*
Reason for selection of NGC 891: Explicit prototype; Milky Way analog; Sb morphology congruent with Green Valley; most cited edge-on spiral within 30 Mpc
Caveats about selection of NGC 891: Star-formation too high for Green Valley: twice MW, possibly due only to nuclear starburst (Kennicutt 1998a; Popescu et al. 2004; Whaley et al. 2009), MW may have similar starbust episodes every 30 Myr (Krumholz et al. 2017)
Notes on NGC 891: Morpohological type: Sb (RC3,K13)
Works where NGC 891 referred to as prototype: Hughes et al. (2014)
General works about NGC 891: Hughes et al. (2014); Mouhcine et al. (2010)

Relationship to SETI: Intragalactic broadcasts within disk plane of spiral galaxies (c.f., Benford et al. 2010)

1.9.2.4 Green dwarf galaxies

Dwarf transitional galaxy: Phoenix dwarf [411]

Abbreviations for type: dT; dTr
Type also known as: Dwarf transient galaxy (K13); dE/dIrr (Ferguson & Binggeli 1994); dIrr/dE; dIrr/dSph (Mateo 1998; M12)
Type description: Intermediate type between dwarf spheroidal and dwarf irregular, evolving from one type to the other
Type references: Sandage & Hoffman (1991)

Phoenix dwarf *is sidereal source*
Reason for selection of Phoenix dwarf: Explicit prototype; well-studied (most cited of I17); nearby example; in I17
Works where Phoenix dwarf referred to as prototype: Ferguson & Binggeli (1994)
Works relating Phoenix dwarf to type: van de Rydt et al. (1991); Battaglia et al. (2012)
Phoenix dwarf in I17

1.9.3 Main sequence (blue) galaxies

The blue main sequence galaxies are very diverse. Most star-forming galaxies (SFGs) have a characteristic specific star formation rate (sSFR = SFR/$M_\star$), which varies with mass (Brinchmann et al. 2004; Whitaker et al. 2014; Leja et al. 2015; Lee et al. 2015). The characteristic SSFR is referred to as the "main sequence" of star-forming galaxies in the literature (Noeske et al. 2007; Elbaz et al. 2011; Renzini & Peng 2015). The SFG main sequence evolves strongly with cosmic time, with the SSFR being almost a hundred times greater at high redshift (Noeske et al. 2007; Whitaker et al. 2012; Speagle et al. 2014), reflecting epoch-dependent mass accretion from the intergalactic medium (Bouché et al. 2010; Genzel et al. 2010). They are the most numerous class of galaxy with stellar masses above $10^7\ M_\odot$, but they are presently rare among the most massive galaxies and at $z \lesssim 1$ contain only a minority of the stellar mass (Baldry et al. 2012; Muzzin et al. 2013; Ilbert et al. 2013). Note the characteristic sSFR decreases with time since the Big Bang (Speagle et al. 2014): a galaxy that would be classified as main sequence at $z \sim 2$ would be considered a starburst now, and thus their $z \sim 0$ analogs are placed among the starbursts.

In the present Universe, they tend to be spirals (if large) or irregulars (if small), while at high-redshift they had chaotic morphologies. The overall surface brightness is typically an exponential disk (Wuyts et al. 2011). We classify the $z \sim 0$ Prototypes coarsely by morphology (see below for discussion of fine morphology types), with a few subtypes each of late spirals and irregulars.

Relationship to SETI: These galaxies have relatively high rates of energetic phenomena that may pose a hazard to complex life, including core-collapse supernovae. They have large amounts of gas and dust, which may be an issue for interstellar travel.

1.9.3.1 Early-type star-forming galaxies

Star-forming elliptical galaxy: NGC 5173 [412]

Type description: Normal elliptical morphology, but lies on the main sequence; about one in four elliptical galaxies with $M_\star \lesssim 10^{9.7}\ M_\odot$ but very rare at high mass; may have been rejuvenated by merger
Type references: Schawinski et al. (2009); Kannappan et al. (2009); Wei et al. (2010); Lee et al. (2015); George (2017)

NGC 5173 *is sidereal source*
Reason for selection of NGC 5173: Moderately well-studied (most cited of lower-mass early-types in Wei et al. 2010); classed as blue in Kannappan et al. (2009); Wei et al. (2010)
Caveats about selection of NGC 5173: SFR relatively low for main sequence, may be Green Valley galaxy, as Salim (2014) classes it
Notes on NGC 5173: SFR: ~ 0.5–$0.6\ M_\odot\ \mathrm{yr}^{-1}$; stellar mass: $1.9 \times 10^{10}\ M_\odot$
Works relating NGC 5173 to type: Vader & Vigroux (1991); Wei et al. (2010)
General works about NGC 5173: Erroz-Ferrer et al. (2013)

Blue cored dwarf elliptical galaxy: IC 225 [413]

Type description: Dwarf elliptical with very concentrated core of blue stars that may dominate color; core formed in recent star formation episode; about one in six dEs

Caveats about type: May overlap with blue compact dwarfs to some extent, depending on faintness of underlying disk
Type references: De Rijcke et al. (2003); Gu et al. (2006); Lisker et al. (2006a); Ann et al. (2015)

IC 225 *is sidereal source*
Reason for selection of IC 225: Explicitly cited as example in Gu et al. (2006); A15 classifies it as such; lies on main sequence
Notes on IC 225: SFR: ~ 0.025 $M_\odot$ yr^{-1}; stellar mass: $10^{7.92}$ $M_\odot$; has high metallicity HII region
Works relating IC 225 to type: Gu et al. (2006)
General works about IC 225: Peeples et al. (2008)

Relationship to SETI: Stojković et al. (2019) evaluates IC 225 as habitable, recommends SETI searches

1.9.3.2 Main sequence spiral galaxies

Spiral galaxies, the majority of large MS galaxies in the present Universe, have rich and complex morphologies, prompting numerous classification schemes that prioritize different traits.

Most systems share a sequence from early to late spirals: early-types are redder and have large bulges and loose arms, late-type spirals are bluer and have small bulges and tightly-wound arms, the latest types have no bulges and irregular arms. This seems to be related to galaxy evolution on the main sequence, where young spiral galaxies start out small and star-forming, accrete mass and form stars, growing redder, before reaching a mass threshold where star-formation quenches and the spiral transitions across the main sequence (Schiminovich et al. 2007; Schawinski et al. 2014; Bremer et al. 2018).

The schemes diverge in considering further dimensions of morphology. The traditional Hubble tuning fork classes galaxies into barred (SA) or unbarred (SAB), in parallel sequences, and this is still widely used (de Vaucouleurs et al. 1991; Graham 2019). van den Bergh (1976) instead classes disk galaxies in terms of spiral arms strength, with lenticulars, "anemics", and spirals forming parallel sequences (van den Bergh 1976; Kormendy & Bender 2012). Yet there are many other obvious morphological features in disk galaxies: rings, pseudo-rings, lenses, spiral arms, and more, all with a number of forms. Each feature adds another dimension to parameter space, resulting in lengthy types for each galaxy in some systems: Buta et al. (2015) gives NGC 4258's type as (R'L)SAB(rs,nb)ab, for example.

We are therefore faced with combinatorial explosion. It is impractical to include one of every type of spiral galaxy, especially if we do this for multiple classification systems. An additional concern is that a galaxy's classification, even within the same system, may be judged differently according to different papers. To simplify matters, we concentrate on the early to late sequence. Furthermore, we ignore fine gradations, as these are frequently inconsistent. Instead, we broadly lump galaxies into Sa to Sab, Sb to Sbc, Sc to Scd, Sd to Sdm, and Sm types. Sa-ab and Sb-bc are classified as Green Valley types; the rest are here in the main sequence section. Then, we have a classification by morphology section later, with examples of galaxies with each type of feature with no regard to their star-formation rate. Note we do not include prototypes for unbarred and barred spirals along the early/late sequence; many of the bright, nearby galaxies are only weakly barred, and the presence of a bar does not seem to affect star formation rate in the disk (Kennicutt 1998b).

Consistency between classifications is a prime consideration when choosing prototypes. We especially rely on RC3 and B15. Both use extensions of the de Vaucoleurs system; the former uses optical images and the latter NIR-to-MIR images from *Spitzer* Buta et al. (2015).

General references: Hubble (1926); van den Bergh (1976); Elmegreen & Elmegreen (1982); Buta et al. (2010); Kormendy & Bender (2012); Buta et al. (2015); Graham (2019)

Sc-cd spiral galaxy: M101 [414]

Type description: Spiral galaxy with small bulges; blue galaxy

M101 *is sidereal source*
M101 also known as: NGC 5457
Reason for selection of M101: Extremely well-studied; consistent classification in RC3, K13, A15, B15; not extremely large on sky; in I17
Notes on M101: Morphological type: SAB(rs)cd (RC3), Scd (K13), SABcd (A15), SAB(rs)cd (B15)
General works about M101: Beaton et al. (2019)
M101 in I17
Relationships between M101 and other Exotica Catalog objects: Contains within projected sky region: M101 ULX-1 [311]

Alternative prototype(s): M33: Sc(d) galaxy, in Local Group, in I17 – large on sky

Sd-dm spiral galaxy: NGC 300 [415]

Type description: Spiral galaxy with minimal or no bulge

NGC 300 *is sidereal source*
Reason for selection of NGC 300: Well-studied; nearest to the Local Group; usually classed as Sd
Caveats about selection of NGC 300: M12 lists as Sc
Notes on NGC 300: Morphological type: SA(s)d (RC3); Sc (M12); Sd (K13); SA(s)dm (B15); neighbor of NGC 55

Sm spiral galaxy: NGC 55 [416]

Type also known as: Magellanic spiral galaxy
Type description: Spiral/irregular galaxy with no bulge; hints of spiral structure in form of single arm; can be barred or unbarred
Notes on type: Some schemes would place as irregular galaxies

NGC 55 *is sidereal source*
Reason for selection of NGC 55: Well-studied; close to Local Group; classed as Sm by RC3, B15
Caveats about selection of NGC 55: Classification somewhat uncertain because nearly edge-on; K13 classes it as Sdm
Notes on NGC 55: Morphological type: SB(s)m edge-on (RC3), Sdm (K13), SAB(s)m sp (B15); neighbor of NGC 300

Alternative prototype(s): Large Magellanic Cloud: explicit prototype, nearest example, extremely well-studied, in I17 – too large on sky to cover with a few observations

Dwarf Sc-Scd spiral: NGC 4701 [417]

Notes on type: Sm and Sd spiral galaxies tend to be dwarfs

NGC 4701 *is sidereal source*
Reason for selection of NGC 4701: Classed as dwarf spiral in Das et al. (2019b)
Caveats about selection of NGC 4701: Luminosity is $> 10^9$ $L_\odot$ in NED, possibly too high to be dwarf; B15 classes as Sbc
Notes on NGC 4701: Morphological type: SA(s)cd (RC3), SA(s)$\underline{\text{b}}$c (B15)
Works relating NGC 4701 to type: Das et al. (2019b)

Super spiral galaxy: SS 16 [418]

Notes on type: Spiral galaxy with vigorous star formation despite $M_\star > 10^{11}$ $M_\odot$; large diameter; bulge-to-total ratios comparable to Sc spirals; on main sequence or are starbursts
Type references: Ogle et al. (2016)

SS 16 *is sidereal source*
Reason for selection of SS 16: One of closest and most luminous; studied in detail by Ogle et al. (2016)
Notes on SS 16: SFR: 10 $M_\odot$ yr^{-1}; stellar mass: 1.5×10^{11} $M_\odot$; would lie on Whitaker et al. (2012) main sequence if extrapolated, somewhat high for extrapolated Speagle et al. (2014) main sequence
Works relating SS 16 to type: Ogle et al. (2016)

Alternative prototype(s): UGC 2885: large (120 kpc diameter) Sc galaxy, relatively well-studied (Rubin et al. 1980; Roelfsema & Allen 1985) – not big enough to be Ogle et al. (2016) super spiral

Cluster late spiral galaxy: M99 [419]

Notes on type: Late-type spiral galaxy in dense environment of galaxy cluster

M99 *is sidereal source*
M99 also known as: NGC 4254
Reason for selection of M99: Most cited in Binggeli et al. (1985a) Virgo cluster catalog with morphology Sc or later
Notes on M99: Morphological classification: SA(s)c (RC3), SAcd (A15), SA(s)c pec (B15)
Relationships between M99 and other Exotica Catalog objects: Within the sky region occupied by: Virgo Cluster [506]

Edge-on Sc-Sd galaxy: NGC 4631 [420]

NGC 4631 *is sidereal source*

Reason for selection of NGC 4631: Most cited late-type edge-on galaxy in RC3

Notes on NGC 4631: Morphological type: SB(s)d edge-on (RC3), Sd (K13), Scd (A15), SB(s)d sp pec (B15)

Relationship to SETI: Intragalactic broadcasts within disk plane of spiral galaxies (c.f., Benford et al. 2010)

1.9.3.3 Irregular galaxies

We exclude disturbed galaxies like M82 that are peculiar because of phenomena like starbursts (see amorphous galaxies in Section 1.9.3.4). In the present Universe, irregular galaxies are primarily dwarfs. These are essentially dE/dSph galaxies with ongoing star formation and high gas fractions (Ferguson & Binggeli 1994), as demonstrated by the smooth disks of old stars they have in the infrared and their overall exponential disk profile (van Zee 2000). We include them among the main sequence galaxies to distinguish them from Blue Compact Dwarfs.

In order to cover a wider range of galaxy sizes, we artificially divide the dwarf irregulars into two size classes, which loosely correspond to the similarly artificial dwarf elliptical and dwarf spheroidal division.

Relationship to SETI: Irregular galaxies are low metallicity, and can be expected to have few planets; they are poor from a conventional galactic habitability standpoint.

Irregular (dE/Magellanic-size): NGC 6822 [421]

NGC 6822 *is sidereal source*

Reason for selection of NGC 6822: In Local Group; relatively small on sky ($2.7'$ half-light radius); stellar mass similar to dEs NGC 185 and NGC 205; surface brightness similar to NGC 205; not tidally distorted

Notes on NGC 6822: Morphological type: IB(s)m (RC3), Im (K13); on main sequence; stellar mass: 1.7×10^8 $M_\odot$; star-formation rate: 0.06 $M_\odot\,yr^{-1}$ (Hα, Mateo 1998), 0.01 $M_\odot\,yr^{-1}$ (MIR; Jarrett et al. 2019), 0.005–0.014 $M_\odot\,yr^{-1}$ (radio, assuming far-infrared–radio correlation holds; Tarchi et al. 2020)

General works about NGC 6822: Schruba et al. (2017); McConnachie (2012)

NGC 6822 in I17

Alternative prototype(s): Small Magellanic Cloud: closest and most well-studied – too big on sky

Irregular (dSph-size): IC 1613 [422]

IC 1613 *is sidereal source*

Reason for selection of IC 1613: In Local Group; among most cited irregular galaxies

Notes on IC 1613: Morphological type: IB(s)m (I17), Im (K13); stellar mass: 3.8×10^7 $M_\odot$; star-formation rate: 0.003 $M_\odot\,yr^{-1}$ (Hα, Mateo 1998), < 0.01 $M_\odot\,yr^{-1}$ (MIR; Jarrett et al. 2019), 0.001–0.004 $M_\odot\,yr^{-1}$ (radio, assuming far-infrared–radio correlation holds; Tarchi et al. 2020)

General works about IC 1613: Madore et al. (2018); Mateo (1998); Skillman et al. (2014)

IC 1613 in I17

1.9.3.4 Other low-redshift types

Amorphous galaxy (main sequence): NGC 3077 [423]

Type also known as: Irr II galaxy

Type description: Apparent irregular morphology due to extended regions of star-formation; high surface brightness "sheets" of unresolved starlight obscured by dust lanes, but lacking the clumpiness of irregular galaxies

Notes on type: This class can include both starbursts (M82) and main sequence galaxies; the term has been used to describe dwarf starburst like Blue Compact Dwarfs (Gallagher & Hunter 1987; Marlowe et al. 1999), but this applies to dwarf amorphous galaxies and not the larger ones

Type references: Sandage & Brucato (1979); Hunter et al. (1994); Hogg et al. (1998)

NGC 3077 *is sidereal source*

Reason for selection of NGC 3077: Nearby, not starburst; one of the original examples of Sandage & Brucato (1979); second most cited of Hogg et al. (1998) sample after starburst M82

General works about NGC 3077: Davidge (2004)

1.9.3.5 High redshift main sequence galaxies

Most star formation at high redshift took place in main sequence galaxies unlike those found today. These were far more dust-obscured and luminous, with luminous infrared galaxies (LIRGs; $L_{\rm IR} > 10^{11}$ L$_\odot$) dominating when $z \gtrsim 1$, and ultraluminous infrared galaxies (ULIRGs; $L_{\rm IR} > 10^{12}$ L$_\odot$) dominating when $z \gtrsim 2$ (Daddi et al. 2007a; Elbaz et al. 2011). The ordered morphology sequences of the present day were largely absent in the early Universe; most main sequence galaxies at $z \gtrsim 1$ had a chaotic, knotty morphology distinct from quiescents, with giant star-forming clumps (Genzel et al. 2011).

The primary classification of SFGs in the early Universe is by a combination of their luminosity and the method they were found. The latter corresponds to criteria on the overall spectral energy distribution (SED). These classes, as used in the literature, have a fair degree of overlap. Furthermore, because these classses are determined by observational selection rather than some theory-motivated cut, they can include a mixture of main sequence and starburst galaxies.

We strive to include the most commonly referred to SFG classes, but we also focus on gravitationally lensed galaxies to boost our sensitivities. Often we were unable to find a prototype that was both unambiguously main sequence and gravitationally lensed. Entries are further grouped into intermediate ($z \sim$ 1–1.5) and high ($z \gtrsim 2$) redshifts, then approximately in order of increasing luminosity. In some cases we were unable to find a likely candidate of a common class of high-redshift galaxies (particularly, no lensed main sequence Lyman α Emitters or main sequence Lyman Break Galaxies).

Relationship to SETI: May have been dangerous for complex life because of higher supernova rate, and large amounts of gas and dust would have hindered interstellar travel. Planets may have existed in massive, high-metallicity galaxies.

LIRG ($z \sim 1$): SGAS J143845.1+145407 [424]

Notes on type: Typically luminous star-forming galaxy at $z \sim 1$

SGAS J143845.1+145407 *is sidereal source*

Reason for selection of SGAS J143845.1+145407: Example of lensed galaxy

Notes on SGAS J143845.1+145407: Redshift: 0.82; magnification: 11.8; SFR: 28 M$_\odot$ yr^{-1}; stellar mass: 6×10^{10} M$_\odot$

Works relating SGAS J143845.1+145407 to type: Dunham et al. (2019)

Spiral galaxy ($z \sim 1.5$): Sp1149 (A1) [425]

Sp1149 (A1) *is sidereal source*

Reason for selection of Sp1149 (A1): Remarkable grand design spiral at relatively high redshift; lensed; well-studied due to multiply-imaged supernova (Kelly et al. 2015) and microlensing of single blue supergiant (Kelly et al. 2018)

Notes on Sp1149 (A1): Redshift: 1.5; magnification: 23; the A1 refers to which lens image being targeted

Works relating Sp1149 (A1) to type: Yuan et al. (2011); Di Teodoro et al. (2018)

General works about Sp1149 (A1): Zitrin & Broadhurst (2009); Smith et al. (2009a)

BzK-type ULIRG ($z \sim 1.5$): A68-HLS115 [426]

Type description: Typical main sequence ULIRG at $z \sim 1.5$; star formation rates ~ 100 M$_\odot$ yr^{-1}; gas mass approximately equal to stellar mass, $\sim (3\text{–}10) \times 10^{10}$ M$_\odot$

Notes on type: BzK refers to cut on $(B - z)$ and $(z - K)$ color

Type references: Daddi et al. (2004, 2008, 2010)

A68-HLS115 *is sidereal source*

Reason for selection of A68-HLS115: Lensed example of galaxy with similar properties

Caveats about selection of A68-HLS115: Not explicitly identified as BzK galaxy

Notes on A68-HLS115: Redshift: 1.6; magnification: 4.5; infrared luminosity: $\sim 10^{12}$ L$_\odot$; ultraviolet luminosity: 2×10^{10} L$_\odot$; specific star-formation rate: 3 Gyr^{-1}

General works about A68-HLS115: Girard et al. (2018)

Lyman Alpha Emitter: *See starburst galaxies.*

Lyman Break Galaxy: *See starburst galaxies.*

Main sequence submillimeter galaxy: HLock-01 (R) [427]

Abbreviations for type: SMG

Type description: Ultraluminous SFG at $z \gtrsim 2$ with high 850 μm flux; among brightest galaxies but on main sequence; submillimeter emission from dust-obscured star formation concentrated compared to outlying optical disks; submillimeter effective radii ~ 1 kpc

Notes on type: Close pairs of dust-obscured main sequence galaxies can be blended into apparent single SMG by single-dish instruments

Type references: Michałowski et al. (2010); Hayward et al. (2011); da Cunha et al. (2015); Hodge et al. (2016); Miettinen et al. (2017)

HLock-01 (R) *is sidereal source*

Reason for selection of HLock-01 (R): Likely MS galaxy; lensed; high star-formation rate

Notes on HLock-01 (R): Redshift: 3.0; magnification: 8; SFR: 1,500$M_\odot$ yr^{-1}; stellar mass: 5×10^{11} $M_\odot$; specific star-formation rate: 3 Gyr^{-1}; hyperluminous infrared galaxy (HyLIRG); forms close pair with unobscured Lyman break galaxy

General works about HLock-01 (R): Marques-Chaves et al. (2018)

Dust Obscured Galaxy: *See AGNs.*

1.9.4 Starbursts

Galaxies (or regions of galaxies) with high specific star-formation rates due to a short episode of star formation. Informally, has been used to describe any galaxy with high star-formation rate, but we only include galaxies with SFR exceeding the main sequence by a significant factor. These only account for $\sim 10\%$ of the cosmic star formation. The starburst regions tend to be compact, and are generally triggered by the sudden influx of gas.

We group them into nuclear starbursts occurring in the centers of larger galaxies, and dwarf starbursts occurring in small galaxies. We also specifically include some relatively nearby starbursts noted to have properties analogous to high-z galaxies, in addition to some lensed starbursts at high redshift, to further constrain the possibility that habitability evolves with time.

General references: Elbaz et al. (2011); Sargent et al. (2012)

Relationship to SETI: Starburst regions are likely to be dangerous for evolving complex life, because of the high rate density of supernovae and other explosive events and high radiation fluxes. Interstellar travel is also likely to be difficult because of radiation and high densities of gas and dust. Highly technological ETIs might harness the enormous available power, however.

1.9.4.1 Nuclear starbursts

Luminous starbursts in present Universe found in centers of medium to large galaxies. There is no real classification system for nuclear starbursts. Infrared luminosity divides them into sub-LIRGs, LIRGs, and ULIRGs, although the thresholds are somewhat arbitrary. We use infrared optical depth, which is correlated with gas mass, surface density, and star formation rate, to group them and span the range of starbursts.

General references: Thompson et al. (2005)

Infrared-transparent nuclear starburst: M82 [428]

Type description: Starburst transparent to bulk of thermal dust emission, although not to optical-ultraviolet starlight

M82 *is sidereal source*

Reason for selection of M82: Explicit prototype of starbursts; extremely well-studied

Notes on M82: SFR: ~ 8 $M_\odot$ yr^{-1}; starburst triggered by encounter with M81 a few hundred Myr ago; gas and cosmic ray densities hundreds of times higher than Milky Way; striking wind

Works where M82 referred to as prototype: Seaquist & Odegard (1991); O'Connell et al. (1995); Shopbell & Bland-Hawthorn (1998); Naylor et al. (2010); Leroy et al. (2015)

Works relating M82 to type: O'Connell et al. (1995)

General works about M82: Dalcanton et al. (2009); O'Connell et al. (1995); Strickland & Heckman (2009); Shopbell & Bland-Hawthorn (1998); Leroy et al. (2015); Lacki et al. (2011)

Relationships between M82 and other Exotica Catalog objects: Contains within projected sky region: 43.78+59.3 [745], M82 X-1 [310], M82 X-2 [312]

Alternative prototype(s): NGC 253: roughly same distance – less intense; NGC 4945: roughly same distance – also Seyfert

Blackbody nuclear starburst: Arp 220 [360]

Type description: Starburst region with photosphere; optical depth greater than 1 at far-infrared wavelengths; tend to be nuclei in ULIRGs
Type references: Sakamoto et al. (2008); Rangwala et al. (2011); Wilson et al. (2014); Barcos-Muñoz et al. (2015); Martín et al. (2016)

Arp 220 *is sidereal source*
Arp 220 also known as: IC 4553
Reason for selection of Arp 220: Explicit prototype of ULIRGs; extreme conditions; very well-studied; elsewhere in catalog
Notes on Arp 220: Star formation concentrated in two 50 pc radius regions, East and West nuclei, each with $\sim 100\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$; molecular gas mass: $\sim 2 \times 10^9\ \mathrm{M}_\odot$; temperature within nuclei ~ 80 K; cosmic ray energy density more than one thousand times local Milky Way
Works where Arp 220 referred to as prototype: Smith et al. (1998); Wilson et al. (2014); Martín et al. (2016)
Works relating Arp 220 to type: Downes & Solomon (1998); Sakamoto et al. (2008); Barcos-Muñoz et al. (2015)
General works about Arp 220: Smith et al. (1998); Sakamoto et al. (2008); Scoville et al. (2015); Downes & Solomon (1998); Yoast-Hull et al. (2015); Wilson et al. (2014); Barcos-Muñoz et al. (2015)

Relationship to SETI: High ambient temperatures in starburst may affect giant planet formation (Thompson 2013)

1.9.4.2 High-z main sequence galaxy analogs

Lyman Break Analog: Arp 236 [429]

Abbreviations for type: LBA
Type description: LIRG with low metallicity, tend to have lower dust obscuration; merging small galaxies with $\mathrm{M}_\star \sim 10^{10}\ \mathrm{M}_\odot$; similar to Lyman break galaxies at high redshift
Type references: Overzier et al. (2008)

Arp 236 *is sidereal source*
Arp 236 also known as: VV 114
Reason for selection of Arp 236: Given example in Grimes et al. (2006); well-studied
Notes on Arp 236: Star-formation rate: $\sim 50\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$; consists of two galaxies, VV 114 East (a UV-bright galaxy) and VV 114 (an infrared-bright galaxy with a nuclear starburst); Hoopes et al. (2007) classifies it as a compact Ultraviolet Luminous Galaxy (UVLG)
Works relating Arp 236 to type: Grimes et al. (2006)
General works about Arp 236: Grimes et al. (2006)

BzK analog ($z \sim 0$): HIZOA J0836-43 [430]

Type description: Low-redshift LIRG with widespread star-formation over a large disk; high galaxy-wide stellar and gas mass, gas fraction (~ 0.5), and star-formation rate ($\gg 10\ \mathrm{M}_\odot\,\mathrm{yr}^{-1}$); global properties similar to BzK galaxies at $z \sim 1$–2
Notes on type: Galaxies with these properties would be on the main sequence at $z \sim 1$–2, but are starbursts because they happen to exist at $z \sim 0$

HIZOA J0836-43 *is sidereal source*
Reason for selection of HIZOA J0836-43: Known nearby example, similarity to BzK galaxies remarked upon.
Notes on HIZOA J0836-43: HI mass: $7.5 \times 10^{10}\ \mathrm{M}_\odot$; stellar mass: $4.4 \pm 1.4 \times 10^{10}\ \mathrm{M}_\odot$; star-formation rate: $35\ \mathrm{M}_\odot\,\mathrm{yr}^{-1}$ (radio, infrared; Donley et al. 2006),$20\ \mathrm{M}_\odot\,\mathrm{yr}^{-1}$ (infrared; Cluver et al. 2008)
Works relating HIZOA J0836-43 to type: Cluver et al. (2010)
General works about HIZOA J0836-43: Cluver et al. (2010); Donley et al. (2006); Cluver et al. (2008)

1.9.4.3 Dwarf starbursts

Dwarf starburst occur in dwarf irregular galaxies, with low metallicity and little dust.

Blue compact dwarfs: I Zwicky 18 [431]

Abbreviations for type: BCD
Type description: Very compact star-forming region hosted in low surface brightness dwarf galaxies; appear like extragalactic HII regions; very blue and strong emission lines; low metallicity
Type references: Izotov & Thuan (1999); Gil de Paz et al. (2003); Meyer et al. (2014)

I Zwicky 18 *is sidereal source*
I Zwicky 18 also known as: Mrk 116; CGPG 0930.5+5527
Reason for selection of I Zwicky 18: Explicit prototype; very well-studied (most cited of Thuan 1983); one of two originally presented in Sargent & Searle (1970)
Caveats about selection of I Zwicky 18: Very low metallicity, even for BCDs (Gil de Paz et al. 2003); appears to lack older host, unlike most BCDs (Papaderos & Östlin 2012) – Annibali et al. (2013) reports old stars
Notes on I Zwicky 18: SFR: ~ 1 M$_\odot$ yr^{-1}; stellar mass: $\sim 2 \times 10^6$ M$_\odot$
General works about I Zwicky 18: Annibali et al. (2013); Papaderos & Östlin (2012)

Alternative prototype(s): II Zw 40 (UGCA 116) – other original BCD of Sargent & Searle (1970), fourth most cited galaxy in Gil de Paz et al. (2003) sample after IC 10, I Zw 18, and NGC 1705, explicit prototype of dwarf starbursts (Galliano et al. 2005; Kepley et al. 2014) – highly obscured by Galactic dust (Gil de Paz et al. 2003)

Ultracompact blue dwarf: POX 186 [432]

Type description: Extremely compact star-forming region/galaxy; smaller than typical BCD, with typical radii $\lesssim 1$ kpc
Notes on type: Not to be confused with Ultracompact dwarf galaxies (UCDs), which resemble compact ellipticals and are thought to be stripped dwarf galaxy nuclei
Type references: Corbin et al. (2006)

POX 186 *is sidereal source*
Reason for selection of POX 186: Among most extreme properties known; early discovery
Works relating POX 186 to type: Doublier et al. (2000); Guseva et al. (2004); Corbin et al. (2006)
General works about POX 186: Doublier et al. (2000); Guseva et al. (2004)

Lyman α Emitter ($z \sim 0$): Haro 2 [433]

Type also known as: Lyman Alpha Emitter
Type description: Identified by Lyman α line emission, similar to intensely star-forming galaxies at high redshift
Notes on type: At low redshift, these include luminous blue compact dwarfs

Haro 2 *is sidereal source*
Reason for selection of Haro 2: Explicit prototype; well-studied
Notes on Haro 2: Loose & Thuan (1986) considers it a prototype of nE BCDs which consists of a tiny nuclear starburst within a faint dwarf elliptical galaxy
Works where Haro 2 referred to as prototype: Otí-Floranes et al. (2012)
General works about Haro 2: Loose & Thuan (1986)

Green Pea: NGC 2366 [434]

Type description: Small, luminous starburst galaxies with extremely bright [OIII] lines; effective radii of ~ 1 kpc; stellar masses of $\sim 10^8$–10^{10} M$_\odot$; specific star-formation rates ~ 1–100 Gyr^{-1}
Notes on type: [OIII] emission showed up as green for $0.1 < z < 0.3$ Green Peas in SDSS images, hence name; smaller local versions of Green Peas have been dubbed Blueberry galaxies (Yang et al. 2017a)
Type references: Cardamone et al. (2009); Micheva et al. (2017)

NGC 2366 *is sidereal source*
Reason for selection of NGC 2366: Identified as Green Pea by Micheva et al. (2017); nearby
Works relating NGC 2366 to type: Micheva et al. (2017)

1.9.4.4 High redshift starbursts

Dwarf starburst ($z \sim 3$): ID11 [435]

ID11 *is sidereal source*
Reason for selection of ID11: Lensed example
Notes on ID11: Redshift: 3.1; magnification: 35; stellar population age < 20 Myr; stellar mass: $< 10^7$ $M_\odot$; effective radius: 62 pc; analogous to BCD
Works relating ID11 to type: Vanzella et al. (2016)

Lyman α emitter starburst ($z \sim 2$): SL2S J02176-0513 [436]

Abbreviations for type: LAE
Type also known as: Lyman Alpha Emitter starburst
Type description: Identified by Lyman α line emission; generally small high-redshift star-forming galaxy; stellar masses of 10^8–10^9 $M_\odot$ ($z \sim$ 2–3), $\lesssim 10^{10}$ $M_\odot$ ($z \sim$ 4–6), $\lesssim 10^8$ $M_\odot$ ($z \sim 7$); star-formation rates of $\sim$ 1–10 $M_\odot$ yr^{-1} ($z \sim$ 2–3; are starbursts at $z \gtrsim 7$)
Notes on type: LAEs can be either main sequence or starburst; we did not find a lensed LAE that we were confident was main sequence in the literature
Type references: Cowie & Hu (1998); Gawiser et al. (2006, 2007); Lai et al. (2007, 2008); Finkelstein et al. (2009); Bayliss et al. (2010); Ono et al. (2010)

SL2S J02176-0513 *is sidereal source*
Reason for selection of SL2S J02176-0513: Lensed example
Notes on SL2S J02176-0513: Redshift: 1.8; magnification: 17; star-formation rate: 20 $M_\odot$ yr^{-1}; stellar mass: $\sim (1\text{–}2) \times 10^8$ $M_\odot$; two components with effective radius $\sim$ 300 pc
General works about SL2S J02176-0513: Brammer et al. (2012); Berg et al. (2018)

Alternative prototype(s): BG J1429+1202A – much brighter than typical LAEs (Marques-Chaves et al. 2017); SDSS J101129.49+014323.3: slightly higher magnification (Bolton et al. 2006) – further, poorly studied

Lyman Break Galaxy starburst ($z \sim 3$): cB 58 [437]

Abbreviations for type: LBG
Type description: Identified by minimal ultraviolet emission bluewards of 912 Åin rest frame; larger than LAEs and dusty; wide range of stellar masses (including $\gtrsim 10^{10}$ $M_\odot$)
Type references: Steidel et al. (1996); Sawicki & Yee (1998); Papovich et al. (2001); Pettini et al. (2001)

cB 58 *is sidereal source*
Reason for selection of cB 58: First discovered highly lensed example; well-studied
Caveats about selection of cB 58: SFR only about three to four times main sequence expectation for stellar mass
Notes on cB 58: Redshift: 2.7; magnification: ~ 50 (about half of galaxy); stellar mass: 4.4×10^9 $M_\odot$; gas mass: $\sim 5 \times 10^9$ $M_\odot$; SSFR: 8 Gyr^{-1}; also a LIRG
Works relating cB 58 to type: Baker et al. (2004); Siana et al. (2008)
General works about cB 58: Seitz et al. (1998); Wuyts et al. (2012); Siana et al. (2008); Riechers et al. (2010); Yee et al. (1996); Dessauges-Zavadsky et al. (2015)

Starburst submillimeter galaxy ($z \sim 2$): SMM J2135-0102 [438]

Abbreviations for type: SMG
Type description: Ultraluminous SFG at $z \gtrsim 2$ with high 850 μm flux; small stellar mass and high specific star-formation rate; submillimeter emission from dust-obscured star formation concentrated compared to outlying optical disks; submillimeter effective radii $\sim$ 1 kpc
Type references: Tacconi et al. (2008); Hayward et al. (2011); da Cunha et al. (2015); Hodge et al. (2016); Miettinen et al. (2017)

SMM J2135-0102 *is sidereal source*
SMM J2135-0102 also known as: The Eyelash

Reason for selection of SMM J2135-0102: Well-studied; lensed example; likely starburst
Caveats about selection of SMM J2135-0102: SFR only about three times main sequence expectation for stellar mass
Notes on SMM J2135-0102: Redshift: 2.3; magnification: 37.5; SFR: (210–250) $M_\odot$ yr^{-1}; stellar mass: 3×10^{10} $M_\odot$ yr^{-1}; molecular gas mass: (1–4) $\times 10^{10}$ $M_\odot$
Works relating SMM J2135-0102 to type: Swinbank et al. (2010)
General works about SMM J2135-0102: Swinbank et al. (2010, 2011); Zhang et al. (2018); Danielson et al. (2013)

Alternative prototype(s): SPT 0538-50: clearly starburst, most cited lensed SMG in Ma et al. (2015), high magnification (Bothwell et al. 2013) – relatively poorly studied

1.9.4.5 Jet-induced starburst

Jet-induced starburst: Minkowski's Object [439]

Type description: Starburst triggered when AGN jet compresses large amount of intergalactic gas, or gas in struck satellite galaxy

Minkowski's Object *is sidereal source*
Minkowski's Object also known as: Arp 133
Reason for selection of Minkowski's Object: Explicit prototype
Notes on Minkowski's Object: SFR: 0.5 $M_\odot$ yr^{-1}; stellar mass: 2×10^{7} $M_\odot$; dwarf starburst along NGC 541's jet
Works where Minkowski's Object referred to as prototype: Elbaz et al. (2009)
Works relating Minkowski's Object to type: Croft et al. (2006); Lacy et al. (2017)

1.9.5 Low surface brightness galaxies

This category is for galaxies with low surface brightnesses which are very low surface brightness for their stellar mass and type. A typical dwarf spheroidal would not qualify, for example, because its low surface brightness is expected for its small stellar mass.

Relationship to SETI: Have been suggested to be cloaked Type III societies (Zackrisson et al. 2015), although the expected infrared waste heat is lacking.

1.9.5.1 Giant low surface brightness galaxies

Giant low surface brightness galaxy: Malin 1 [440]

Abbreviations for type: GLSB
Type description: Early-type spiral or lenticular surrounded by big, massive neutral gas disks; extended disks have gas masses of $\sim 10^{10}$ $M_\odot$, few stars, scale lengths of ~ 10 kpc and possibly much bigger, and spiral arms; surface brightness comparable to dwarf spheroidal
Type references: Sprayberry et al. (1995); Matthews et al. (2001); Galaz et al. (2015)

Malin 1 *is sidereal source*
Reason for selection of Malin 1: Explicit prototype; first recognized; well-studied
Notes on Malin 1: SFR: $\sim$ 1–2 $M_\odot$ yr^{-1}; inner disk is lenticular with scale length 5 kpc; outer disk scale length 40 kpc, diameter 160–200 kpc (one of largest known), gas mass 7×10^{10} $M_\odot$
Works where Malin 1 referred to as prototype: Barth (2007); Lelli et al. (2010); Boissier et al. (2016)
Works relating Malin 1 to type: Barth (2007); Lelli et al. (2010); Galaz et al. (2015); Boissier et al. (2016)

1.9.5.2 Ultradiffuse Galaxies

Galaxy class that have large radii but small stellar masses. Their nature is debated: whether they are massive galaxies where star formation was quenched or dwarf galaxies that got puffed out.

Abbreviation for general class: UDGs

General references: Sandage & Binggeli (1984); Binggeli et al. (1985b); van Dokkum et al. (2015, 2016); Beasley & Trujillo (2016); Amorisco & Loeb (2016); Chamba et al. (2020)

Red ultradiffuse galaxy: VCC 1287 [441]

Type description: Quiescent UDG; stellar mass: $\sim 10^{7}$–10^{9} $M_\odot$; effective radius: $\sim$ 1.5–10 kpc; old, metal-poor stellar population; typically though not always found in galaxy clusters

Type references: van Dokkum et al. (2015); Mihos et al. (2015); Koda et al. (2015); Muñoz et al. (2015); Kadowaki et al. (2017); Pandya et al. (2018); Gu et al. (2018); Román et al. (2019)

VCC 1287 *is sidereal source*

Reason for selection of VCC 1287: Studied in depth by Beasley et al. (2016) and Pandya et al. (2018); nearby, in Virgo Cluster

Works relating VCC 1287 to type: Beasley et al. (2016); Pandya et al. (2018)

Relationships between VCC 1287 and other Exotica Catalog objects: Within the sky region occupied by: Virgo Cluster [506]

Alternative prototype(s): Dragonfly 44: more cited, in van Dokkum et al. (2015) sample – further, in Coma Cluster

Blue ultradiffuse galaxy: UGC 2162 [442]

Type description: Gas-rich galaxies; stellar mass: $\lesssim 10^9$ $M_\odot$, larger gas mass; effective radius of a few kpc; typically found in the field and groups; may be progenitor of red UDG

Type references: Merritt et al. (2016); Román & Trujillo (2017); Trujillo et al. (2017); Spekkens & Karunakaran (2018)

UGC 2162 *is sidereal source*

Reason for selection of UGC 2162: Identified by Trujillo et al. (2017) as nearest example

Notes on UGC 2162: SFR: 0.01 $M_\odot$ yr^{-1}; stellar mass: 2×10^7 $M_\odot$

Works relating UGC 2162 to type: Trujillo et al. (2017)

General works about UGC 2162: Hunter & Elmegreen (2004)

Almost dark galaxies: HI 1232+20 [443]

Type description: Extremely gas rich galaxy ($M_{gas}/M_\star \sim$ 10–100) with very small but non-zero stellar population; several kpc wide; extreme version of blue UDG

Type references: Janowiecki et al. (2015); Ball et al. (2018); Mihos et al. (2018)

HI 1232+20 *is sidereal source*

Reason for selection of HI 1232+20: One of best studied; one component is elsewhere in catalog

Notes on HI 1232+20: Three objects, most massive is Coma P; properties very uncertain because distance debated (Anand et al. 2018b; Brunker et al. 2019); Coma P stellar mass: $\sim 10^6$ $M_\odot$; Coma P HI mass: $\sim 3 \times 10^7$ $M_\odot$; other two components have no stars and have one-sixth and one-fourth mass

Works relating HI 1232+20 to type: Janowiecki et al. (2015); Ball et al. (2018)

General works about HI 1232+20: Anand et al. (2018b); Brunker et al. (2019)

Relationships between HI 1232+20 and other Exotica Catalog objects: Contains within projected sky region: AGC 229385 [634]

Relationship to SETI: Noted as resembling Kardashev III society in Zackrisson et al. (2015)

1.9.6 Disturbed galaxies

Disturbed galaxies is a category to collect galaxies that have been disturbed by interaction with external forces: tidal interactions, galaxy collisions, accretion of cold intergalactic gas, or ram pressure from a surrounding dense medium. These three classes have diverse and unrelated origins.

1.9.6.1 Ring galaxies

Ring galaxies are galaxies with an inner component surrounded by a large, typically bright annulus of baryonic matter. Few & Madore (1986) divides ring galaxies into the P-type, where the ring is formed by galaxy interactions, and the O-type, where the ring is formed by internal processes. The presentation of O-types is deferred to the galaxy morphology section. Polar and Hoag-type ring galaxies are neither P-type nor O-type.

General references: Few & Madore (1986)

Collisional ring galaxy: Cartwheel galaxy [444]

Type also known as: P-type ring galaxy

Type description: Formed when one galaxy pierces center of another's disk, drawing in gas that then rebounds and launches density wave outwards; ring has high star-formation rate for several hundred Myr, but is off-center; projectile galaxy visible nearby

Type references: Lynds & Toomre (1976); Hernquist & Weil (1993); Marston & Appleton (1995); Mapelli et al. (2008)

Cartwheel galaxy *is sidereal source*
Reason for selection of Cartwheel galaxy: Explicit prototype; striking morphology; well-studied
Notes on Cartwheel galaxy: Thin blue outer ring is starbursting, surrounds red bulge-like component, connected by spoke-like features
Works where Cartwheel galaxy referred to as prototype: Appleton & Marston (1997); Parker et al. (2015)
Works relating Cartwheel galaxy to type: Hernquist & Weil (1993)
General works about Cartwheel galaxy: Hernquist & Weil (1993); Higdon (1995); Fosbury & Hawarden (1977)

Polar ring galaxy: NGC 4650A [445]

Type also known as: Polar disk galaxy
Type description: Ring/disk orthogonal to inner component's rotation, in polar orbits; inner component is lenticular or elliptical;, while ring/disk is bluer and star-forming; may form by galaxy collisions, galaxy encounters, or misalignment between galaxy rotation axis and accreted IGM gas, with misalignment scenario gaining evidence
Type references: Schweizer et al. (1983); Bekki (1998); Gallagher et al. (2002); Stanonik et al. (2009); Spavone et al. (2010); Coccato et al. (2014); Iodice et al. (2015)

NGC 4650A *is sidereal source*
Reason for selection of NGC 4650A: Explicit prototype; striking morphology; one of six highest-quality polar ring galaxies in Whitmore et al. (1990)
Works where NGC 4650A referred to as prototype: Iodice et al. (2002); Karataeva et al. (2004)
Works relating NGC 4650A to type: Schweizer et al. (1983); Whitmore et al. (1990)

Alternative prototype(s): NGC 6822: much closer, elsewhere in catalog (Demers et al. 2006) – less striking morphology

Hoag-like ring galaxy: Hoag's Object [446]

Type description: Red diskless elliptical surrounded by nearly perfectly symmetrical blue star-forming ring; enigmatic and unclear evolution, may be result of elliptical accreting cold HI from IGM; extremely rare
Type references: Brosch (1985); Schweizer et al. (1987); Finkelman et al. (2011)

Hoag's Object *is sidereal source*
Reason for selection of Hoag's Object: Eponym and explicit prototype; one of few examples known; striking morphology
Notes on Hoag's Object: Warped ring of HI surrounds blue optical ring
Works where Hoag's Object referred to as prototype: Finkelman et al. (2011)
General works about Hoag's Object: Brosch et al. (2013)

Alternative prototype(s): UGC 4599: possible closer example (Finkelman & Brosch 2011)
Relationship to SETI: Voros (2013) speculated that these are result of ETI astroengineering

1.9.6.2 Interacting galaxies

Dopita et al. (2002) classify interactions on a roughly chronological sequence with five stages: (1) isolation, (2) minimally interacting, (3) interacting with moderate tidal features, (4) heavily distorted pairs that retain separate galaxy nuclei, and (5) advanced mergers. We focus here on stages 3 and 4, when the tidal features are most striking. These features include tidal tails, long streamers of gas and stars; and bridges that appear to link two galaxies of very unequal masses (Toomre & Toomre 1972; Barnes & Hernquist 1992a).

General references: Toomre & Toomre (1972); Barnes & Hernquist (1992a); Dopita et al. (2002)

Interacting galaxies: M51a/b [447]

Type description: Visibly disturbed by tides during close passage, though won't necessarily lead to merger; stage 3 in Dopita et al. (2002) sequence

M51a/b *is sidereal source*
Reason for selection of M51a/b: Nearby; well-studied (most cited of Toomre & Toomre 1972); one of four discussed in depth by Toomre & Toomre (1972); in I17
Notes on M51a/b: Large spiral (NGC 5194, M51a) and small lenticular (NGC 5195, M51b); bridge appears to extend from one of M51a's spiral arms to M51b; Lanz et al. (2013) classes as stage 3

M51a/b in I17
Relationships between M51a/b and other Exotica Catalog objects: Contains within projected sky region: M51a [453]
Relationships between M51a/b and objects in I17: Contains within projected sky region: NGC 5195

Major merger: The Antennae [448]

Type description: Galaxies taking final plunge towards each other as they coalesce, with stars and gas mixing; galaxies are roughly equal in mass; stage 4 in Dopita et al. (2002) sequence

The Antennae *is sidereal source*
The Antennae also known as: NGC 4038/4039
Reason for selection of The Antennae: Explicit prototype; very well studied; one of four discussed in depth by Toomre & Toomre (1972)
Notes on The Antennae: Heavily warped disk galaxies; intense triggered star formation; name refers to extremely long tidal tails curving out of system; Lanz et al. (2013) classes as stage 4
Works where The Antennae referred to as prototype: Mirabel et al. (1992); Whitmore et al. (2010)
General works about The Antennae: Whitmore et al. (1999)
Relationships between The Antennae and other Exotica Catalog objects: Adjacent on sky to (sharing parent object with): Antennae TDG [449]

Tidal dwarf galaxy: Antennae TDG [449]

Abbreviations for type: TDG
Type description: Graviationally bound collection of stars and gas born out of tidal tails; expcted to lack dark matter; excess molecular gas
Type references: Mirabel et al. (1992); Barnes & Hernquist (1992b, 1996); Braine et al. (2001)

Antennae TDG *is sidereal source*
Reason for selection of Antennae TDG: First recognized; host elsewhere in catalog
Notes on Antennae TDG: Is star-forming dIrr galaxy
Works relating Antennae TDG to type: Mirabel et al. (1992)
General works about Antennae TDG: Schweizer (1978)
Relationships between Antennae TDG and other Exotica Catalog objects: Adjacent on sky to (sharing parent object with): The Antennae [448]

Dumbbell galaxy: 3C 75 [450]

Type description: Elliptical galaxy envelope containing two cores, due to galaxy merger
Type references: Wirth et al. (1982); Valentijn & Casertano (1988); Parma et al. (1991); Barnes & Hernquist (1992a)

3C 75 *is sidereal source*
3C 75 also known as: NGC 1128
Reason for selection of 3C 75: Highly-cited, elsewhere in catalog
General works about 3C 75: Molnar et al. (2017b); Owen et al. (1985)

Alternative prototype(s): NGC 326: explicit prototype

1.9.6.3 Ram pressure modified galaxies

Galaxies experiencing a headwind as they move through dense medium, which can push gas out of galaxy through ram pressure stripping. The phenomenon tends to occur in galaxy clusters.

General references: Gunn & Gott (1972); Abadi et al. (1999)

Jellyfish galaxies: ESO 137-001 [451]

Type description: Disk galaxies with long gas column trailing out of them; trails can have stringy, knotted appearance in optical images from triggered star formation
Type references: Sun et al. (2007); Smith et al. (2010); Ebeling et al. (2014)

ESO 137-001 *is sidereal source*
Reason for selection of ESO 137-001: Explicit and implicit prototype; explicitly called jellyfish galaxy by Bellhouse et al.

(2017); Jáchym et al. (2019)
Notes on ESO 137-001: Falling into rich Norma cluster; has primary tail and secondary tail, observed in X-rays, Hα, and CO emission
Works where ESO 137-001 referred to as prototype: Fumagalli et al. (2014); Fossati et al. (2016)
Works relating ESO 137-001 to type: Sun et al. (2007, 2010); Jáchym et al. (2014); Fumagalli et al. (2014); Fossati et al. (2016)

Fireball tail galaxy: IC 3418 [452]

Type description: Galaxy with extragalactic HII regions trailing them, in ram-pressured stripped tail; HII regions have cometary appearance and host star formation; may be descendants of jellyfish galaxies
Type references: Yoshida et al. (2008); Hester et al. (2010); Kenney et al. (2014); Poggianti et al. (2017)

IC 3418 *is sidereal source*
Reason for selection of IC 3418: Relatively nearby, in Virgo Cluster; several studies of fireballs
Notes on IC 3418: Host galaxy morphological type: dIrr; tail is 17 kpc long
General works about IC 3418: Kenney et al. (2014); Fumagalli et al. (2011); Hester et al. (2010)

Alternative prototype(s): RB199: first recognized (Yoshida et al. 2008) – further; ESO 137-001: hosts fireballs according to Jáchym et al. (2019)

1.9.7 Galaxy morphological features

This section includes galaxies with morphological features driven by global-scale internal processes, particularly resonances.

1.9.7.1 Spiral arm types

Spiral arms can appear to fall in different classes at different wavelengths. We have chosen prototypes that are consistent in infrared (as judged by Buta et al. 2015) and optical.

General references: Elmegreen & Elmegreen (1982)

Grand design spiral: M51a [453]

Type description: Two arms wound in a logarithmic spiral from bulge to edge of disk

M51a *is sidereal source*
Reason for selection of M51a: Very striking; well studied; classed as grand design by Buta et al. (2015); system elsewhere in catalog; in I17
M51a in I17
Relationships between M51a and other Exotica Catalog objects: Within the sky region occupied by: M51a/b [447]
Relationships between M51a and objects in I17: Adjacent on sky to (sharing parent object with): NGC 5195

Flocculent spiral: NGC 7793 [454]

Type description: Disk densely packed with numerous filamentary, short arms
Type references: Elmegreen & Elmegreen (1982)

NGC 7793 *is sidereal source*
Reason for selection of NGC 7793: Explicit prototype; appears flocculent in infrared images (Buta et al. 2010; Elmegreen et al. 2011; Buta et al. 2015)
Works where NGC 7793 referred to as prototype: Elmegreen & Elmegreen (1982)
NGC 7793 in I17

Leading spiral arm galaxy: NGC 4622 [455]

Type description: End of each spiral arm points in direction of rotation; rare; would pose challenge to theories of spiral arm formation
Caveats about type: Iye et al. (2019) disputes existence of class

NGC 4622 *is sidereal source*
Reason for selection of NGC 4622: Best candidate; only one of two not completely ruled out in Iye et al. (2019), depending on

which side of galaxy is closer to Earth
Works relating NGC 4622 to type: Buta et al. (2003); Byrd et al. (2008)

Anemic spiral galaxy: M91 [456]

Type description: Galaxy with low contrast between arms and rest of disk; intermediate between normal spirals and lenticulars
Type references: van den Bergh (1976)

M91 *is sidereal source*
M91 also known as: NGC 4548
Reason for selection of M91: Implicit prototype; consistently classed as anemic (or anaemic) by van den Bergh (1976); Weżgowiec et al. (2007); Vollmer et al. (2012)
Notes on M91: SFR: 0.74 $M_\odot$ yr^{-1}; specific SFR: 0.01 Gyr^{-1} (one half of Milky Way; Green Valley); morphological type: SB(rs)b (RC3)
Works relating M91 to type: Vollmer et al. (2012)
General works about M91: Weżgowiec et al. (2007); Boselli et al. (2015)
Relationships between M91 and other Exotica Catalog objects: Within the sky region occupied by: Virgo Cluster [506]

1.9.7.2 Planar morphologies

Both spiral and lenticular galaxies can host a variety of morphological structures besides spiral arms. Buta et al. (2015) describes a great variety of types, as part of the S^4G effort to classify galaxy morphologies using near/mid-infrared *Spitzer* images. They occur at three basic scales, also called varieties: nuclear (parsec scale, in galaxy's nucleus); inner (kiloparsec scale, just outside bulge and bar); and outer (surround main disk and spiral arms). Galaxies can have several features of each variety, or of the same type and variety (e.g., two outer rings). These structures are related to resonances within a disk galaxy induced by radial asymmetries in a galaxy, especially by a bar, which rotate at some pattern speed.

There are several types of features. *Bars* are boxy structures surrounded by underdense galaxies, most commonly running through a disk galaxy's bulge. *Lenses* are disk structures with radial symmetry, constant or slowly declining surface brightness profiles, and sharp edges. *Barlenses* are bright disks with lens-like morphology that occur within bars, but are not bulges. *Rings* are annular structure with radial symmetry with sharp inner and outer edges. *Pseudorings* are annular structures that are broken into arcs instead of a complete circle. *Plumes* are little secondary arms that stick out of the base of a major arm. *Nuclear spirals* are spiral patterns that occur entirely within the galactic nucleus. Readers are referred to Buta et al. (2015) for more in depth discussion about classification.

We chose Prototypes mainly based on having consistent morphological types between de Vaucouleurs et al. (1991), Karachentsev et al. (2013), Ann et al. (2015), and Buta et al. (2015). Some galaxies here are prototypes for several types to minimize the number of galaxies observed.

The types are listed roughly in increasing distance from the galactic center.

General references: Binney & Merrifield (1998); Comerón et al. (2014); Buta et al. (2015)

Nuclear ring morphology: NGC 1097 [457]

NGC 1097 *is sidereal source*
Reason for selection of NGC 1097: Explicit example (implicit prototype) in B15 Table 1; classification in C14 and B15
Notes on NGC 1097: Morphological type: (R)SB(rs,nr)ab pec (C14), (R')SB(rs,nr)ab pec (B15)
Works where NGC 1097 referred to as prototype: Buta et al. (2015)

Nuclear lens morphology: M64 [458]

M64 *is sidereal source*
M64 also known as: NGC 4826
Reason for selection of M64: Classification in C14, B15; in I17; elsewhere in catalog
Notes on M64: Morphological type: (R)SA(rs,r,nl)a (C14), (RL,R')SA(rs,r,nl)0/a (B15)
General works about M64: Rubin (1994); Watkins et al. (2016); Braun et al. (1992); Rix et al. (1995); Braun et al. (1994)
M64 in I17

Double bar (nuclear bar) morphology: NGC 1291 [459]

Type description: Galaxy containing bar with much smaller bar centered on nucleus
Notes on type: Common in early-type barred galaxies
Type references: Erwin (2004); Buta et al. (2015); Méndez-Abreu et al. (2019)

NGC 1291 *is sidereal source*
Reason for selection of NGC 1291: First identified; in Erwin (2004) catalog; considered as "important spiral galaxy" in McQuinn et al. (2017); given as prominent example in Buta et al. (2015)
Notes on NGC 1291: Morphological type: (R)SB(s)0/a (RC3), (R)SAB(l,nb)0^+ (C14), (R)SAB(l,bl,nb)0^+ (B15)
Works where NGC 1291 referred to as prototype: Buta et al. (2015)
Works relating NGC 1291 to type: de Vaucouleurs (1975); Méndez-Abreu et al. (2019)

Barlens morphology: NGC 2787 [460]

NGC 2787 *is sidereal source*
Reason for selection of NGC 2787: Classification in C14, B15; noted as good example (implicit prototype) in B15; in I17; elsewhere in catalog
Notes on NGC 2787: Morphological type: (L)SB_a(r,bl)0^0 (C14), $SA\underline{B}_a$($\underline{r}$s,bl)0^+ (B15)
Works where NGC 2787 referred to as prototype: Buta et al. (2015)
General works about NGC 2787: Buta et al. (2015)
NGC 2787 in I17

Strong bar morphology: NGC 1365 [461]

NGC 1365 *is sidereal source*
Reason for selection of NGC 1365: Explicit example in B15 Table 1; striking example; classification in RC3, C14, B15
Notes on NGC 1365: Morphological type: SB(s)b (RC3), (R')SB(r$\underline{s}$,nr)bc (C14,B15)
Works where NGC 1365 referred to as prototype: Buta et al. (2015)
General works about NGC 1365: Buta et al. (2015); Risaliti et al. (2009, 2005); Nardini et al. (2015); Parker et al. (2014)
Relationships between NGC 1365 and other Exotica Catalog objects: Within the sky region occupied by: Fornax Cluster [505]

x_1 **ring morphology:** NGC 6012 [462]

Type description: Emerges from pattern of stellar orbits near strong bar; not resonant; not circularly symmteric, but roughly outline bar

NGC 6012 *is sidereal source*
Reason for selection of NGC 6012: Implicit prototype in B15; explicit example in B15 Table 1; classification in C14, B15
Notes on NGC 6012: Morphological type: (R)SB(r)ab: (RC3), (R)SB(r,x_1r)ab (C14), (R')SB($\underline{r}$l,x_1r)ab (B15)
Works where NGC 6012 referred to as prototype: Buta et al. (2015)
Works relating NGC 6012 to type: Regan & Teuben (2004)

Inner ring morphology: NGC 1433 [463]

NGC 1433 *is sidereal source*
Reason for selection of NGC 1433: Called "textbook example" of outer, inner, and nuclear rings in Buta (1984); explicit example (implicit prototype) in B15 Table 1; classification in RC3, C14, B15; elsewhere in catalog
Notes on NGC 1433: Morphological type: (R')SB(r)ab (RC3), (R_1)SB(r,nr,ab)a (C14), (R_1')SB(p,r,bl,nr,nb)a (B15)
Works where NGC 1433 referred to as prototype: Buta (1984); Buta et al. (2015)
General works about NGC 1433: Buta et al. (2015); Buta (1984)

Plume morphology: NGC 1433 [463]

Type description: Secondary spiral arms bracketing the main arms

NGC 1433 *is sidereal source*
Reason for selection of NGC 1433: Implicit prototype in Buta (1984); explicit example in B15 Table 1; classification in C14,

B15; elsewhere in catalog
Notes on NGC 1433: Morphological type: (R')SB(r)ab (RC3), (R_1)SB(r,nr,nb)a (C14), (R_1')SB(p,r,bl,nr,nb)a (B15)
Works where NGC 1433 referred to as prototype: Buta (1984); Buta et al. (2015)
General works about NGC 1433: Buta et al. (2015); Buta (1984)

Outer lens morphology: NGC 2787 [460]

NGC 2787 *is sidereal source*
Reason for selection of NGC 2787: Explicit example in B15 Table 1; classification in C14, B15; in I17; elsewhere in catalog
Notes on NGC 2787: Morphological type: (L)SB_a(r,bl)0^0 (C14), SA$\underline{B}_a$($\underline{r}$s,bl)0^+ (B15)
Works where NGC 2787 referred to as prototype: Buta et al. (2015)
General works about NGC 2787: Buta et al. (2015)
NGC 2787 in I17

Outer pseudoring morphology: NGC 1365 [461]

NGC 1365 *is sidereal source*
Reason for selection of NGC 1365: Explicit example (implicit prototype) in B15 Table 1; classification in C14, B15
Notes on NGC 1365: Morphological type: SB(s)b (RC3), (R')SB(r$\underline{s}$,nr)bc (C14,B15)
Works where NGC 1365 referred to as prototype: Buta et al. (2015)
General works about NGC 1365: Buta et al. (2015); Risaliti et al. (2009, 2005); Nardini et al. (2015); Parker et al. (2014)
Relationships between NGC 1365 and other Exotica Catalog objects: Within the sky region occupied by: Fornax Cluster [505]

Outer Lindblad ring: NGC 5101 [464]

NGC 5101 *is sidereal source*
Reason for selection of NGC 5101: Explicit example of subtype in B15 Table 1; classification in C14, B15
Notes on NGC 5101: Morphological type: (R)SB(rs)0/a (RC3), (R_1R_2')SB($\underline{r}$s,nl?)0/a (C14), (R_1R_2')SB($\underline{r}$s,bl)0/a (B15)
Works where NGC 5101 referred to as prototype: Buta et al. (2015)

Double outer ring: NGC 3898 [465]

NGC 3898 *is sidereal source*
Reason for selection of NGC 3898: Explicit example in B15 Table 1; classification in C14, B15
Notes on NGC 3898: Morphological type: SA(s)ab (RC3), (RR)SA0^+ (C14, B15)
Works where NGC 3898 referred to as prototype: Buta et al. (2015)

1.9.7.3 Other morphologies

Counterrotating disk galaxy: M64 [458]

Type description: One component of galaxy spins the opposite way of the rest, retrograde and not polar/perpendicular (unlike polar ring/disk)
Type references: Rubin (1994)

M64 *is sidereal source*
M64 also known as: NGC 4826
Reason for selection of M64: Well-studied; elsewhere in catalog
Notes on M64: Stellar disk and inner part of gas disk rotate one way, outer regions of gas disk in opposite way; possibly result of merger
Works relating M64 to type: Braun et al. (1992, 1994); Rubin (1994); Rix et al. (1995)
General works about M64: Rubin (1994); Watkins et al. (2016); Braun et al. (1992); Rix et al. (1995); Braun et al. (1994)
M64 in I17

Superthin disk galaxy: UGC 7321 [466]

Type description: Stellar disk's scale height less than 1/10 of scale length; can be result of abnormally small scale height

or abnormally large scale length
Type references: Goad & Roberts (1981); van der Kruit et al. (2001); Banerjee & Jog (2013)

UGC 7321 *is sidereal source*
Reason for selection of UGC 7321: Explicit prototype; one of Goad & Roberts (1981)'s original sample
Notes on UGC 7321: Viewed edge on; axis ratio: 10–14; stellar scale height: $\sim$ 150 pc, abnormally thin; HI scale height not superthin
Works where UGC 7321 referred to as prototype: Banerjee & Jog (2013)
Works relating UGC 7321 to type: Matthews (2000); Uson & Matthews (2003)
General works about UGC 7321: Uson & Matthews (2003)
Relationships between UGC 7321 and other Exotica Catalog objects: Within the sky region occupied by: Virgo Cluster [506]

Alternative prototype(s): IC 5249: more massive, has abnormally long disk scale-length instead (van der Kruit et al. 2001)

Shell galaxy: NGC 3923 [467]

Type description: Shells are stellar structures found in early-type galaxies; formed during mergers; can be nested concentrically, may only be sections of spheres

NGC 3923 *is sidereal source*
Reason for selection of NGC 3923: One of early examples; used by Binney & Merrifield (1998) as example; extreme example
Notes on NGC 3923: At least 42 nested (partial) shells of varying contrast levels, the most known
Works relating NGC 3923 to type: Malin & Carter (1980); Bílek et al. (2016)

Rectangular galaxies: LEDA 074886 [468]

Type description: Early-type galaxy with unusually boxy isophotes
Type references: Jarvis (1987); Graham et al. (2012)

LEDA 074886 *is sidereal source*
Notes on LEDA 074886: Size similar to Small Magellanic Cloud; has stellar disk in center, possibly result of merger
Works relating LEDA 074886 to type: Graham et al. (2012)

Alternative prototype(s): IC 3370: early discovery, larger – much further away (Jarvis 1987)

1.9.8 Environmental classifications

Void galaxy: KK 246 [469]

Type description: Found deep in center of cosmological voids; usually small dwarf, more often blue and star-forming than expected with high gas fractions, although red void galaxies are known; otherwise normal
Type references: Rojas et al. (2004); Patiri et al. (2006); Kreckel et al. (2012)

KK 246 *is sidereal source*
Reason for selection of KK 246: One of nearest examples, in Local Void; extremely isolated, $\gtrsim$ 3 Mpc from other known galaxies; fairly well-studied for void galaxy
Works relating KK 246 to type: Kreckel et al. (2011); Rizzi et al. (2017)
General works about KK 246: Kreckel et al. (2011)

Brightest cluster galaxy: NGC 6166 [390]

Abbreviations for type: BCG
Type also known as: Brightest cluster member (BCM)
Type description: Usually large, red ellipticals, often though not always cD subtype; usually at the greatest depths of cluster gravitational potential; on average, abnormally luminous and massive, probably due to accretion of other large cluster galaxies
Type references: Schechter (1976); Lin & Mohr (2004); De Lucia & Blaizot (2007); Coziol et al. (2009)

NGC 6166 *is sidereal source*
Reason for selection of NGC 6166: Elsewhere in catalog; clear BCG of Abell 2199 (Minkowski 1961)
General works about NGC 6166: Morgan & Lesh (1965); Bertola et al. (1986); Bender et al. (2015)

Alternative prototype(s): M49: BCG of Virgo Cluster – only BCG by a small margin over M87, not cD

Satellite galaxy: NGC 205 [398]

Type description: Small galaxy gravitationally bound to single larger primary galaxy

NGC 205 *is sidereal source*

NGC 205 also known as: M110

Reason for selection of NGC 205: Nearby; well-studied; smaller on sky than Magellanic Clouds; already in catalog

Notes on NGC 205: M_V: -16.5; M31 satellite

General works about NGC 205: McConnachie et al. (2005); McConnachie (2012)

Relationships between NGC 205 and other Exotica Catalog objects: Adjacent on sky to (sharing parent object with): (GC) 037-B327 [610], M31-EC4 [341], M32 [396], G1 [609]

Relationships between NGC 205 and objects in I17: Gravitationally bound to: M31

1.10 Active galactic nuclei

A phylum covering the central black holes of galaxies and the phenomena they power. We include quiescent central black holes too, although they are generally not considered "active"; however, these can nonetheless display small flares when examined closely enough. The luminosity of these objects is powered by accretion onto the black hole. Outflows are also an important component of some of these objects, including particle-filled jets and bubbles.

Active galactic nuclei have a huge number of classification systems (Padovani et al. 2017). Like high-redshift galaxies, these tend to be based on observational criteria in different parts of the spectrum. The types overlap significantly; the same AGN may be classified as a Seyfert and a LINER, for example. We have chosen what we understand to be the most important classes based on their widespread use, and/or their ability to capture physically important distinctions between the AGNs.

According to the unification models, AGNs have roughly the same structures, although their luminosity varies, with the different types being the result of different orientation (Antonucci 1993; Urry & Padovani 1995). The reality is likely more complicated, although the basic idea is still common (Elitzur 2012). There is certainly a distinction between AGNs with jets (radio galaxies, radio-loud quasars, blazars, some Seyferts and LINERs) and those lacking them (radio-quiet quasars, some Seyferts and most LINERs). Padovani et al. (2017) proposes that another fundamental axis being between "low excitation" (LINERs, some XBONGs, most FR I radio galaxies, BL Lac blazars) and "high excitation" AGNs (Seyferts, most FR II radio galaxies, quasars). This distinction is not directly included here.

Additional classes were added to cover objects with unusual spectral or morphological features, or the presence of multiple supermassive black holes. A few auxiliary objects related to AGNs have also been included: megamasers and AGN relics (a voorwerp and a fossil AGN).

Abbreviation for general class: AGN

General references: Antonucci (1993); Urry & Padovani (1995); Elitzur (2012); Netzer (2015); Padovani et al. (2017)

1.10.1 Intermediate mass black holes

Many theories predict a class of intermediate mass black holes (IMBHs) masses in the range 100–10^6 $M_\odot$, some of which grew into supermassive black holes (e.g., Madau & Rees 2001; Portegies Zwart et al. 2004; Begelman et al. 2006b). These have proven elusive so far, although some dwarf galaxies have scaled-down SMBHs in larger galaxies, with masses of 10^4–10^6 $M_\odot$ (Barth et al. 2004; Greene et al. 2019). On the other end, the gravitational wave event GW 190521 detected by LIGO and Virgo heralded the birth of a ~ 150 $M_\odot$ black hole by the merger of two stellar-mass black holes (The LIGO Scientific Collaboration et al. 2020a,b).

General references: Barth et al. (2004); Greene et al. (2019)

Hyperluminous X-ray source: ESO 243-49 HLX1 [470]

Abbreviations for type: HLX

Type description: X-ray source, luminosity $\gtrsim 10^{42}$ erg s^{-1}; found off-center from host galaxies; best X-ray candidates for IMBHs, although may be extreme interacting binary stars

Type references: Farrell et al. (2009); Lasota et al. (2015); Greene et al. (2019)

ESO 243-49 HLX1 *is sidereal source*

Reason for selection of ESO 243-49 HLX1: Best known example; best X-ray candidate for IMBH according to Greene et al. (2019)

Notes on ESO 243-49 HLX1: Located well-off ESO 243-49's disk, unlike most dwarf galaxy AGNs; surrounded by a small star cluster, possibly nucleus of tidally shredded galaxy, where HLX1 was its former central black hole

Works relating ESO 243-49 HLX1 to type: Farrell et al. (2009); Webb et al. (2012)

General works about ESO 243-49 HLX1: Bellovary et al. (2010); Mapelli et al. (2012); Webb et al. (2010); Farrell et al. (2012)

Alternative prototype(s): 3XMM J215022.4-055108: suspected tidal disruption of star by IMBH in star cluster, with peak luminosity 10^{43} erg s^{-1} and falling off over decade to $\sim 10^{42}$ erg s^{-1} (Lin et al. 2018) – may be given as separate class in future catalog versions

1.10.2 Low luminosity AGNs

Quiescent SMBH: Sgr A* [471]

Type description: Essentially inactive SMBH; detected dynamically or through very low luminosity emission; can have small flares and variability

Notes on type: Large flares about once every 10^5 yr when SMBH tidally disrupts star that comes too close (Rees 1988; Bade et al. 1996; Bloom et al. 2011)

Sgr A* *is sidereal source*

Reason for selection of Sgr A*: Closest example; very well-studied

Notes on Sgr A*: SMBH mass: 4×10^6 M$_{\odot}$; source of weak radio emission; flares in submillimeter and X-rays frequently; indirect evidence implies it was brighter at times during the past, including Seyfert episodes

Works relating Sgr A* to type: Baganoff et al. (2001); Genzel et al. (2003); Shen et al. (2005); Ponti et al. (2010)

General works about Sgr A*: Bland-Hawthorn et al. (2013); Gillessen et al. (2009)

Relationships between Sgr A* and other Exotica Catalog objects: Within the sky region occupied by: Central Cluster [343]; Hosts (is primary of): G2 [669], IRS 16E [604], IRS 16C [668], S0-2 [667], S4711 [574]

Low Ionization Nuclear Emission Region (AGN-powered): NGC 1052 [472]

Abbreviations for type: LINER

Type description: Nucleus with emission line spectra from low-ionization (neutral or singly-ionized) atoms like O I, O II, N II, S II; low-excitation

Caveats about type: Very common, but most can probably be powered by ultraviolet emission from stellar population; we only include those powered by an AGN

Type references: Heckman (1980); Ferland & Netzer (1983); Ho et al. (2001); Alonso-Herrero et al. (2000); Singh et al. (2013)

NGC 1052 *is sidereal source*

Reason for selection of NGC 1052: Explicit prototype; multiwavelength evidence for active SMBH with jet; one of Heckman (1980) original sample

Works where NGC 1052 referred to as prototype: Pogge et al. (2000); Sugai & Malkan (2000); Kadler et al. (2004); Ho (2008)

General works about NGC 1052: Claussen et al. (1998); Lo (2005); Kadler et al. (2004)

NGC 1052 in I17

Dwarf Seyfert: NGC 4395 [473]

Type description: Seyfert galaxy (typically associated with late type galaxies) with low luminosity ($L(\mathrm{H}\alpha) < 10^{40}$ erg s^{-1} in Ho et al. 1997)

Type references: Ho et al. (1997)

NGC 4395 *is sidereal source*

Reason for selection of NGC 4395: Among lowest luminosity Seyferts known; nearby

Notes on NGC 4395: Type I Seyfert

Works relating NGC 4395 to type: Filippenko & Sargent (1989); Moran et al. (1999)

General works about NGC 4395: Brum et al. (2019); Peterson et al. (2005)

1.10.3 XBONGs

X-ray Bright Optically Normal Galaxy: NGC 4686 [474]

Abbreviations for type: XBONG
Type description: AGN with typical bright X-ray emission; no sign of activity in optical light; may be result of radiatively inefficient accretion flow or obscuration
Type references: Comastri et al. (2002); Yuan & Narayan (2004); Civano et al. (2007)

NGC 4686 *is sidereal source*
Reason for selection of NGC 4686: Nearest of four in Smith et al. (2014); one of two identified in Tueller et al. (2010)
Works relating NGC 4686 to type: Tueller et al. (2010); Smith et al. (2014)

Alternative prototype(s): NGC 4992: cited somewhat more – more distant

1.10.4 Seyfert galaxies

Intermediate luminosity AGNs, generally associated with spiral galaxies. Their optical spectra are characterized by optical emission lines from highly ionized atoms, with emission in other bands as well. Historically, they have been divided into Type 1 or Type 2, with intermediate fine-grained classes sometimes added.

General references: Khachikian & Weedman (1974); Osterbrock (1977); Rieke (1978); Elvis et al. (1978); Wilson & Willis (1980); Osterbrock (1981); Malkan & Sargent (1982)

Seyfert 1 galaxy: NGC 7469 [475]

Type description: Seyfert with broad line region – specifically, Balmer emission lines much wider ($\gtrsim$ 1,000 km s^{-1}) than forbidden lines from narrow line region ($\lesssim$ 1,000 km s^{-1}); weak [OIII] relative to Balmer lines
Notes on type: Sometimes taken to include intermediate classes (1.2, 1.5, 1.8, 1.9)
Type references: Khachikian & Weedman (1974); Osterbrock & Pogge (1985)

NGC 7469 *is sidereal source*
Reason for selection of NGC 7469: Only object in Seyfert (1943) sample that is neither Seyfert 1.5 nor Narrow-Line Seyfert 1; well-studied (third most cited of 256 AGNs in Malkan et al. 1998
Works relating NGC 7469 to type: Osterbrock (1977); Malkan et al. (1998)

Seyfert 2 galaxy: NGC 1068 [476]

Type description: Seyfert lacking broad line regions in unpolarizaed optical spectra; strong [OIII] relative to Balmer lines
Notes on type: In most cases, broad line region exists but is hidden by dust; candidate "true Seyfert 2" AGNs have been proposed but their interpretation is challenged (Tran 2001; Bianchi et al. 2019)
Type references: Antonucci & Miller (1985)

NGC 1068 *is sidereal source*
NGC 1068 also known as: M77
Reason for selection of NGC 1068: Extremely well-studied; one of original six Seyferts in Seyfert 1943; elsewhere in catalog
Notes on NGC 1068: First where broad line region was detected through polarized light spectra; obscuring torus directly detected
Works relating NGC 1068 to type: Antonucci & Miller (1985); Levenson et al. (2001); Jaffe et al. (2004)
General works about NGC 1068: Antonucci & Miller (1985); Levenson et al. (2001); Jaffe et al. (2004); Telesco et al. (1984)

Starburst/Seyfert composite galaxy: NGC 1068 [476]

Type description: Galaxy with spectroscopic or X-ray evidence for both Seyfert 2 and nuclear star formation; luminosity of starburst rivals AGN; may represent younger Seyfert 2 AGNs
Type references: Moran et al. (1996); Levenson et al. (2001); Cid Fernandes et al. (2001); Kewley et al. (2006)

NGC 1068 *is sidereal source*
NGC 1068 also known as: M77
Reason for selection of NGC 1068: Extremely well-studied; one of original six Seyferts in Seyfert 1943; elsewhere in catalog
Caveats about selection of NGC 1068: Classification as composite not universal: Cid Fernandes et al. 2001 does not consider it

one, Levenson et al. 2001 does

Works relating NGC 1068 to type: Telesco et al. (1984); Levenson et al. (2001)

General works about NGC 1068: Antonucci & Miller (1985); Levenson et al. (2001); Jaffe et al. (2004); Telesco et al. (1984)

Alternative prototype(s): Mrk 273: ULIRG with both AGN activity and starburst, considered to be composite by Cid Fernandes et al. (2001) and Levenson et al. (2001) – more distant

Narrow line Seyfert 1 galaxy: I Zwicky 1 [477]

Abbreviations for type: NLS1

Type description: Appears to lack broad line regions, but spectra otherwise resemble Seyfert 1 nucleus (e.g., weak [OIII] relative to Balmer lines); broad line regions exists but has narrow velocity dispersion; thought to host small SMBHs with high accretion rate

Type references: Osterbrock & Pogge (1985); Mathur (2000); Huang et al. (2019)

I Zwicky 1 *is sidereal source*

Reason for selection of I Zwicky 1: Explicit prototype; very well-studied

Works where I Zwicky 1 referred to as prototype: Huang et al. (2019)

Works relating I Zwicky 1 to type: Boller et al. (1996); Mathur (2000)

General works about I Zwicky 1: Huang et al. (2019); Vestergaard & Wilkes (2001)

1.10.5 Radio galaxies

Radio galaxies generally have a core, a jet, and a pair of lobes. The relative strength of these components forms the major classification system for the radio galaxies, the Fanaroff-Riley (FR) classes (Fanaroff & Riley 1974).

General references: Fanaroff & Riley (1974); Antonucci & Ulvestad (1985); Barthel (1989); Urry & Padovani (1995)

1.10.5.1 Fanaroff-Riley radio galaxy classes

FR 0 galaxies: NGC 2911 [478]

Type description: Core emits 10–100% of radio emission; jets and lobes on kiloparsec scales or smaller; most common type of radio galaxies, found in most boxy/cored ellipticals

Type references: Balmaverde & Capetti (2006); Baldi & Capetti (2009); Baldi et al. (2015, 2018)

NGC 2911 *is sidereal source*

Reason for selection of NGC 2911: Most cited of FR0CAT (Baldi et al. 2018), most cited of fourteen in Cheng & An (2018)

FR I galaxies: Centaurus A [479]

Type description: Lobe-dominated, lobes brightest in radio near core; generally dimmer than FR II, brighter than FR 0

Relationship with other types: BL Lacs viewed off-axis in standard radio unification

Type references: Fanaroff & Riley (1974); Begelman et al. (1984); Urry & Padovani (1995); Ghisellini & Celotti (2001); Baldi & Capetti (2009)

Centaurus A *is sidereal source*

Centaurus A also known as: NGC 5128

Reason for selection of Centaurus A: Explicit prototype; closest (< 4 Mpc); many studies including gamma-rays

Works where Centaurus A referred to as prototype: Israel (1998)

Works relating Centaurus A to type: Hardcastle et al. (2003); Abdo et al. (2010d)

General works about Centaurus A: Abdo et al. (2010d); Tully et al. (2015); Israel (1998); Hardcastle et al. (2003)

Relationships between Centaurus A and other Exotica Catalog objects: Contains within projected sky region: Cen A outer filament [348]

FR II galaxies: Cygnus A [480]

Type description: Radio lobes are limb-brightened; hotspots at ends of lobes; generally brightest of radio galaxies

Relationship with other types: Radio-loud quasars and flat spectrum radio quasars viewed off-axis in standard radio unification

Type references: Fanaroff & Riley (1974); Begelman et al. (1984); Urry & Padovani (1995); Ghisellini & Celotti (2001)

Cygnus A *is sidereal source*
Reason for selection of Cygnus A: Explicit prototype; extremely well observed as calibrator that anchors radio flux scale (Perley & Butler 2017)
Works where Cygnus A referred to as prototype: Begelman et al. (1984); Perley et al. (1984)
Works relating Cygnus A to type: Perley et al. (1984)

1.10.5.2 Radio galaxy morphological classes

Radio galaxies where lobes, jets, and cores are not collinear, but appear to be bent or split.

Head-tail radio galaxy: NGC 1265 [481]

Type also known as: Radio trail galaxy
Type description: Jets swept back from the core, both in the samedirection, as if has two tails; found in galaxy clusters; possibly result of ram pressure
Notes on type: Distinction exists between narrow angle tails (including NGC 1265) where jets bent strongly in same direction, probably small galaxies; and wide angle tails (prototype: NGC 7720) where jets extend some distance before decollimating into bent lobes, frequently in cD galaxies (Eilek et al. 1984; O'Donoghue et al. 1990; Missaglia et al. 2019)
Type references: Miley et al. (1972); Begelman et al. (1979)

NGC 1265 *is sidereal source*
NGC 1265 also known as: 3C 83
Reason for selection of NGC 1265: Explicit prototype; one of original examples in Miley et al. (1972)
Works where NGC 1265 referred to as prototype: Begelman et al. (1984)
Relationships between NGC 1265 and other Exotica Catalog objects: Within the sky region occupied by: Perseus Cluster [508]; Adjacent on sky to (sharing parent object with): NGC 1275 minihalo [513], NGC 1277 [402]

X-shaped radio galaxy: 3C 403 [482]

Type also known as: Winged radio galaxy
Type description: Has two pairs of radio lobes instead of one; usually a low luminosity FR II or possibly FR I in some cases; uncertain cause, could be ram pressure, dual AGNs, or jet precession
Type references: Leahy & Williams (1984); Kraft et al. (2005); Cheung (2007); Gopal-Krishna et al. (2012)

3C 403 *is sidereal source*
Reason for selection of 3C 403: Explicit prototype; well-studied (third most cited of Cheung 2007); closest
Works where 3C 403 referred to as prototype: Gopal-Krishna et al. (2012)
Works relating 3C 403 to type: Kraft et al. (2005); Gopal-Krishna et al. (2012)
General works about 3C 403: Kraft et al. (2005)

1.10.5.3 Compact radio galaxies

Miniature but bright variant of radio galaxy morphology, with radio lobes contained entirely in host galaxy. They have a peaked radio spectrum, the result of low frequency absorption; more compact examples have a peak at higher frequencies. These are probably young radio galaxies where the jet is still boring out of the galaxy.

General references: Bicknell et al. (1997); O'Dea (1998); Owsianik & Conway (1998); Dallacasa et al. (2000); Murgia (2003); Tinti et al. (2005)

Compact Steep Spectrum sources: 3C 286 [483]

Abbreviations for type: CSS
Type description: Larger ($\sim$ 1–20 kpc) and older ($\sim$ 1 Myr) of compact radio galaxies; radio spectrum peaks below 500 MHz
Type references: Fanti et al. (1995); O'Dea (1998); Snellen et al. (2000)

3C 286 *is sidereal source*
Reason for selection of 3C 286: Extremely well-studied (most cited CSS of Fanti et al. 1995; O'Dea 1998)
Notes on 3C 286: One of two CSSs detected by *Fermi*-LAT (Ackermann et al. 2015)

GHz Peaked Source: PKS 1934-638 [484]

Abbreviations for type: GPS
Type description: Smaller (10–1,000 pc) and younger; spectrum peaks around 1 GHz
Notes on type: Overlap with Compact Symmetric Objects (CSOs), which are similarly small and have triple (lobe-core-lobe) morphology (Readhead et al. 1996); CSOs have ages of $\lesssim$ 10 kyr and are directly observed to grow with VLBI (Owsianik & Conway 1998; Polatidis & Conway 2003; Murgia 2003), although some show signs of ancient activity (Siemiginowska et al. 2002)
Type references: O'Dea et al. (1991); O'Dea (1998)

PKS 1934-638 *is sidereal source*
Reason for selection of PKS 1934-638: Explicit prototype; well-studied (fourth most cited object in O'Dea 1998, second most cited object in O'Dea et al. 1991 after blazar CTA 102)
Works where PKS 1934-638 referred to as prototype: O'Dea (1998)

Relationship to SETI: PKS 1934-638 discussed as possible artificial transmitter in Kellermann (1966); currently no reason to specifically expect it to be inhabited

1.10.6 Quasars

Historically, AGNs where the host galaxy was not detected – but modern telescopes can detect their host galaxies. Now simply AGNs that are exceptionally bright and not viewed directly on the jet-axis; there is no official luminosity threshold for an object to be called a quasar.

Abbreviation for general class: QSO
General references: Schmidt & Green (1983); Elvis et al. (1994); Bahcall et al. (1997); Krolik (1999)

Radio loud quasar: 3C 273 [485]

Type description: Luminous radio galaxies; have jets, broad-line and narrow-line regions; relatively rare ($\sim$ 10% of quasars)
Relationship with other types: Broad-line FR II radio galaxies viewed close to but not directly down jet axis in standard unification theory
Type references: Barthel (1989); Kellermann et al. (1989); Urry & Padovani (1995)

3C 273 *is sidereal source*
Reason for selection of 3C 273: Extremely well-studied (most cited of Palomar Bright Quasar Survey; Schmidt & Green 1983); brightest quasar from Earth; Zhang et al. (2019) calls it "one of the most representative quasars"
Caveats about selection of 3C 273: Impey et al. 1989 calls it a "miniblazar": sub-dominant ($\sim$ 10%) blazar-like component to spectrum
Works relating 3C 273 to type: Courvoisier (1998)
General works about 3C 273: Zhang et al. (2019); Impey et al. (1989); Courvoisier (1998)

Radio quiet quasar: Mrk 335 [486]

Type description: Bright, distant Seyfert 1 galaxies with broad-line and narrow-line regions; faint radio emission
Type references: Kellermann et al. (1989); Laor & Behar (2008)

Mrk 335 *is sidereal source*
Reason for selection of Mrk 335: Nearby; well-studied (seventh most cited object in Palomar Bright Quasar Survey, most cited of radio-quiet objects; Schmidt & Green 1983)
Caveats about selection of Mrk 335: Not universally considered a quasar: too faint in Schmidt & Green (1983); Véron-Cetty & Véron (2010) – considered quasar in Elvis et al. 1994; Blundell & Beasley 1998
Notes on Mrk 335: Radio-to-optical flux density: $\sim$ 0.2, characteristic of radio quiet quasars; also a NLS1

Broad absorption line quasar: Cloverleaf quasar [487]

Type description: Radio-quiet quasar showing blueshifted high-ionization absorption "troughs" (very broadened lines; $\sim 0.1c$) in optical spectrum; probably an orientation effect where we observe quasar along accretion disk wind
Type references: Weymann et al. (1991); Stocke et al. (1992); Elvis (2000)

Cloverleaf quasar *is sidereal source*
Cloverleaf quasar also known as: H 1413+117
Reason for selection of Cloverleaf quasar: Most cited of Stocke et al. (1992); gravitationally lensed
Notes on Cloverleaf quasar: Magnification 11–23
Works relating Cloverleaf quasar to type: Chartas et al. (2004)
General works about Cloverleaf quasar: Chartas et al. (2004); Venturini & Solomon (2003)

Weak line quasar: PHL 1811 [488]

Type description: No or weak forbidden emission lines, but are not blazars; X-ray weak as well, depending on viewing angle; rare, most found at high-z
Type references: Wu et al. (2011); Luo et al. (2015)

PHL 1811 *is sidereal source*
Reason for selection of PHL 1811: Nearby example; well-studied
Notes on PHL 1811: Redshift: 0.19; second brightest quasar in optical with $z > 0.1$; also a NLS1; X-ray underluminous by two orders of magnitude
Works relating PHL 1811 to type: Leighly et al. (2001, 2007b,a)

1.10.7 Blazars

AGNs viewed directly down the axis of a relativistic jet. Their (apparent) luminosity is dominated at all wavelengths by beamed emission from the jet. Their spectrum has two broad peaks or plateaus, one in radio to X-rays and a gamma-ray peak. In the radio, the spectrum is “flat”, where F_ν is harder than $\nu^{-0.5}$. A blazar “main sequence” links luminosity and spectral characteristics They are also strongly variable, including having extreme gamma-ray flares, and their optical light is polarized.

General references: Angel & Stockman (1980); Antonucci & Ulvestad (1985); Makino et al. (1989); Fossati et al. (1998); Wehrle et al. (1998); Ghisellini et al. (1998); Cavaliere & D’Elia (2002); Jorstad et al. (2010); Ghisellini et al. (2011); IceCube Collaboration et al. (2018a); Ackermann et al. (2016a)

BL Lac object: BL Lac [489]

Type description: Optical spectrum lacks emission lines, sometimes a pure continuum; generally fainter than FSRQs
Relationship with other types: FR I radio galaxies viewed on jet axis in standard unification theory
Type references: Stein et al. (1976); Padovani & Giommi (1995); Cavaliere & D’Elia (2002)

BL Lac *is sidereal source*
Reason for selection of BL Lac: Eponym; very well-studied (second most cited of Padovani & Giommi 1995 catalog)
Caveats about selection of BL Lac: Optical spectrum sometimes characteristic of FSRQ (Giommi et al. 2012) – luminosity places it firmly as BL Lac (Ghisellini et al. 2011)

Flat Spectrum Radio Quasar (blazar): 3C 279 [490]

Type also known as: Optically Violent Variable (OVV)
Type description: Optical spectrum has strong broad emission lines, characteristic of quasars; generally brighter than BL Lacs
Caveats about type: Some authors allow for the existence of non-blazar FSRQs where the jet luminosity is subdominant (Impey et al. 1989); others consider all FSRQs as blazars

3C 279 *is sidereal source*
Reason for selection of 3C 279: Very well studied (second most cited in Fossati et al. (1998) after 3C 273); classed as both OVV adn FSRQ
Caveats about selection of 3C 279: Optical spectrum sometimes characteristic of BL Lac (Giommi et al. 2012)
Notes on 3C 279: Has extreme gamma-ray flares
Works relating 3C 279 to type: Maraschi et al. (1992)
General works about 3C 279: Wehrle et al. (1998); Ackermann et al. (2016a); Hartman et al. (1992); Böttcher et al. (2007)

Neutrino blazar: TXS 0506+056 [491]

TXS 0506+056 *is sidereal source*

Reason for selection of TXS 0506+056: Known example of neutrinos detected from blazar

Notes on TXS 0506+056: One of most luminous blazars in local Universe, possibly precondition for bright neutrino emission; low energy spectrum abnormal

Works relating TXS 0506+056 to type: IceCube Collaboration et al. (2018a,b); Padovani et al. (2019)

1.10.8 Dust-obscured galaxies (AGNs)

Many AGNs are obscured by a large column of gas ($N_H \gtrsim 10^{24}$ cm^{-2}), which stops even their X-rays. They are detected by infrared emission (Fabian & Iwasawa 1999; Daddi et al. 2007b; Assef et al. 2015). These levels of obscuration are seen in some nearby Seyfert 2s (Gandhi et al. 2009).

Dust obscured galaxies (DOGs) as a named class are high-redshift galaxies with extreme dust obscuration. Some display NIR bumps in their spectra, and are thought to be extreme starbursts. Others are AGNs.

General references: Dey et al. (2008)

Power-law DOG: SST24 J143644.2+350627 [492]

Type description: Extremely dust obscured; dust is relatively cool; mid-infrared spectrum has power law component presumed to be from AGN; possibly evolutionary step between starbursts and unobscured quasars

Notes on type: Samples selected from *Spitzer* observations

Type references: Dey et al. (2008); Bussmann et al. (2009)

SST24 J143644.2+350627 *is sidereal source*

Reason for selection of SST24 J143644.2+350627: Most cited of Bussmann et al. (2009) sample, though poorly studied overall

Notes on SST24 J143644.2+350627: Redshift: 2.0

Hot DOG: WISE 1814+3412 [493]

Type description: Extremely dust obscured; dust is relatively warm (60–120 K); generally a hyperluminous infrared galaxy (HyLIRG); relatively compact

Notes on type: Samples selected from WISE observations

Type references: Wu et al. (2012, 2014); Assef et al. (2015)

WISE 1814+3412 *is sidereal source*

Reason for selection of WISE 1814+3412: Most cited of Wu et al. (2012) sample, though poorly studied overall

Notes on WISE 1814+3412: First HyLIRG discovered by WISE; also detected in X-rays

Works relating WISE 1814+3412 to type: Wu et al. (2012)

General works about WISE 1814+3412: Eisenhardt et al. (2012); Wu et al. (2012); Stern et al. (2014)

1.10.9 Other AGN classifications

1.10.9.1 Water Megamaser AGNs

AGNs hosting 22 GHz water megamasers, with EIRPs $\gtrsim 100$ L$_\odot$.

General references: Claussen et al. (1984); Lo (2005)

Disk megamaser AGN: NGC 4258 [494]

Type description: Hosts water megamaser in molecular accretion disk surrounding SMBH, ~ 0.2 pc away; chemistry driven by X-rays from AGN

Type references: Neufeld et al. (1994); Miyoshi et al. (1995); Lo (2005)

NGC 4258 *is sidereal source*

NGC 4258 also known as: M106

Reason for selection of NGC 4258: Explicit prototype; very well-studied for Hubble constant measurements; in I17

Works where NGC 4258 referred to as prototype: Lo (2005)

General works about NGC 4258: Herrnstein et al. (1999)

NGC 4258 in I17

Jet-driven megamaser AGN: NGC 1052 [472]

Type description: Hosts water megamaser in molecular clouds impacted by jet; likely driven by shocks from interaction
Type references: Kaufman & Neufeld (1996); Claussen et al. (1998)

NGC 1052 *is sidereal source*
Reason for selection of NGC 1052: First discovered with no additional disk water megamaser; already in catalog; in I17
Works relating NGC 1052 to type: Claussen et al. (1998); Lo (2005)
General works about NGC 1052: Pogge et al. (2000); Sugai & Malkan (2000); Ho (2008); Kadler et al. (2004)
NGC 1052 in I17

1.10.9.2 Changing look AGNs

Changing look AGNs are those whose observed type or state changes over a timescale of years or less, not counting the variability in blazars (LaMassa et al. 2015). It particularly applies to apparent changes in the material obscuring an AGN. Presently, the term "changing look" applies to optical and X-ray transitions (LaMassa et al. 2015).

General references: LaMassa et al. (2015)

Optical changing look AGN: NGC 4151 [495]

Type description: Seyfert with a spectrum that appears to change from Type 1 to Type 2 or back, sometimes with disappearing broad lines

NGC 4151 *is sidereal source*
Reason for selection of NGC 4151: Extremely well-studied
Notes on NGC 4151: Changed from Type 1.5 (Osterbrock 1977) to Type 1.8–2 in 1980s (Lyutyj et al. 1984; Penston & Perez 1984) and back by 1990 (Ayani & Maehara 1991), followed by further transitions (Shapovalova et al. 2008); appears to be related to brightness of accretion disk itself
General works about NGC 4151: Ulrich (2000); Shapovalova et al. (2008)

X-ray changing look AGNs: NGC 1365 [461]

Type description: X-ray obscuration changes from optically thin to optically thin or back; may be result of occulting clouds or changes in accretion disk
Type references: Matt et al. (2003); Bianchi et al. (2009); Risaliti et al. (2009); Parker et al. (2014)

NGC 1365 *is sidereal source*
Reason for selection of NGC 1365: One of original examples in Risaliti et al. (2002); Matt et al. (2003); variation are large; very well-studied; elsewhere in catalog
Notes on NGC 1365: Obscuration fluctuates by factor ~ 3, caused by occultations
Works relating NGC 1365 to type: Risaliti et al. (2005, 2009); Parker et al. (2014)
General works about NGC 1365: Buta et al. (2015); Nardini et al. (2015)
Relationships between NGC 1365 and other Exotica Catalog objects: Within the sky region occupied by: Fornax Cluster [505]

1.10.9.3 Offset AGNs

Wandering AGN: ESO 243-49 HLX1 [470]

Type description: AGN offset from apparent host's center; actually the former SMBH and nucleus of tidally disrupted dwarf companion galaxy, spilled out into larger galaxy's halo
Notes on type: Quiescent wandering SMBHs are seen in ultracompact dwarfs (Seth et al. 2014)
Type references: Governato et al. (1994); Bellovary et al. (2010)

ESO 243-49 HLX1 *is sidereal source*
Reason for selection of ESO 243-49 HLX1: Likely example; explicitly discussed as such by Bellovary et al. (2010); elsewhere in catalog
Works relating ESO 243-49 HLX1 to type: Bellovary et al. (2010); Mapelli et al. (2012)
General works about ESO 243-49 HLX1: Mapelli et al. (2012); Webb et al. (2010); Farrell et al. (2009, 2012); Webb et al. (2012)

1.10.9.4 Multiple AGNs

Galaxies hosting at least two distinct AGNs, each with its own SMBH, as the result of a galaxy merger. Future examples where the SMBHs are very close may be found through their gravitational wave emission.

General references: Begelman et al. (1980); Milosavljević & Merritt (2001, 2003); Merritt et al. (2004); Barack et al. (2019)

Dual AGN: NGC 6240 [496]

Type description: Early stage of evolution; AGNs are of order a kiloparsec apart; SMBHs drawing together by scattering stars around them

Type references: Begelman et al. (1980); Komossa et al. (2003)

NGC 6240 *is sidereal source*

Reason for selection of NGC 6240: Early discovery; well-studied

Notes on NGC 6240: Nuclei seen as distinct sources in X-rays, NIR, and radio; nuclei separted by 700 pc; Kollatschny et al. (2020) claimed a third AGN in NGC 6240, but Treister et al. (2020) could not corroborate it

Works relating NGC 6240 to type: Komossa et al. (2003); Gallimore & Beswick (2004); Max et al. (2007)

Binary AGN: 0402+379 [497]

Type description: SMBHs separation less than ~ 10 pc; rare

Notes on type: Evolution poorly understood in this stage, as there are few stars left to scatter (the "final parsec problem"; Milosavljević & Merritt 2001)

0402+379 *is sidereal source*

Reason for selection of 0402+379: Likely example; possible detection of orbital motion

Notes on 0402+379: VLBI measurements hint at 30,000 year orbital period, would confirm binary status

Works relating 0402+379 to type: Rodriguez et al. (2006); Bansal et al. (2017)

Interacting AGN: OJ 287 [498]

Type description: Binary SMBH where the components are close enough to directly interfere with each other's accretion disks

OJ 287 *is sidereal source*

Reason for selection of OJ 287: Likely example; very well-studied

Notes on OJ 287: Flares in regular pattern, twice every 12 years, with the flares separated by about a year; thought to be a secondary SMBH impacting primary's disk during flares

Works relating OJ 287 to type: Sillanpaa et al. (1988); Lehto & Valtonen (1996); Dey et al. (2019)

General works about OJ 287: Sillanpaa et al. (1996)

Merging jet dual AGN: 3C 75 [450]

Type description: Jets from two AGNs in dual pair collide; can create extreme conditions and possibly generate neutrinos

Type references: Molnar et al. (2017b); Britzen et al. (2019)

3C 75 *is sidereal source*

Reason for selection of 3C 75: Known (possible) example

Caveats about selection of 3C 75: Not entirely clear the jets actually hit, although they do seem to "stick" when they overlap in projection

General works about 3C 75: Molnar et al. (2017b); Owen et al. (1985)

1.10.10 AGN remnants

Voorwerp: Hanny's Voorwerp [499]

Type description: Extragalactic emission nebula ionized by defunct quasar (ionization echo); spectrum dominated by [OIII]

lines
Type references: Lintott et al. (2009); Keel et al. (2012a)

Hanny's Voorwerp *is sidereal source*
Reason for selection of Hanny's Voorwerp: First discovered; most famous
Works relating Hanny's Voorwerp to type: Lintott et al. (2009); Schawinski et al. (2010); Keel et al. (2012b)

Radio fossil: B2 0924+30 [500]

Type description: Radio lobe of defunct radio galaxy; aged cosmic ray electrons still radiating synchrotron at low frequency
Type references: Parma et al. (2007); Brienza et al. (2016)

B2 0924+30 *is sidereal source*
Reason for selection of B2 0924+30: Explicit prototype; one of few confirmed examples
Notes on B2 0924+30: Radio galaxy was active 150–50 Myr ago (Shulevski et al. 2017)
Works where B2 0924+30 referred to as prototype: Jamrozy et al. (2004)
Works relating B2 0924+30 to type: Cordey (1987); Jamrozy et al. (2004); Shulevski et al. (2017)

1.11 Galaxy associations

Analogous to the Stellar groups phylum for stars, this phylum covers collections of galaxies. Objects in this phylum are gravitationally bound and have masses dominated by dark matter. The larger examples, the clusters, include a virialized intracluster medium that dominates the baryonic mass.

The most prominent included edge cases are the binary galaxies, which exclude merging galaxies where hydrodynamic forces are important; fossil groups, which are single galaxies formed from the total merger of the galaxies in a group with a high-entropy ISM/ICM; and the unvirialized protoclusters, which could be fit under the Large-scale structure phylum.

Galaxy associations are mainly classified by richness, from isolated pairs of galaxies through groups and clusters. To the structures themselves, we also included examples of features in the intracluster medium (ICM) of galaxy clusters, both thermal and nonthermal (e.g., Markevitch & Vikhlinin 2007; van Weeren et al. 2019).

1.11.1 Binary galaxies

Binary galaxy: Arp 294 [501]

Type description: Isolated pair of galaxies as small association, no large neighbors nearby, not in advanced stage merger
Type references: Karachentsev (1972); Turner (1976); Hernández-Toledo & Puerari (2001)

Arp 294 *is sidereal source*
Arp 294 also known as: NGC 3786/3788
Reason for selection of Arp 294: Highly cited: second most in Hernández-Toledo & Puerari (2001), which selects for non-merging pairs; no close neighbors
Caveats about selection of Arp 294: Possibly interacting, stage 3 in Lanz et al. (2013); in grouping with two galaxies (Simbad) – distant neighbors, ~ 1 Mpc projected away
Notes on Arp 294: Listed in Karachentsev (1972) and Turner (1976)

Alternative prototype(s): M51: closer, more well-studied – famously interacting, in group with M63 (800 kpc projected away), NGC 5229 (140 kpc projected away, much fainter), big on sky

1.11.2 Dwarf galaxy associations

Dwarf galaxy association: UGCA 319/320 [502]

Type description: Galaxy association/group lacking large galaxies, possibly low mass dark matter halo, compact groups of dwarfs are rare
Type references: Tully et al. (2002, 2006); Stierwalt et al. (2017)

UGCA 319/320 *is sidereal source*
UGCA 319/320 also known as: DDO 161

Reason for selection of UGCA 319/320: Not large on sky; compact; relatively nearby; dedicated paper (Karachentsev et al. 2017)

Notes on UGCA 319/320: Projected separation: 33 kpc projected; Nearest neighbors: KK 176 (1 Mpc away in RV), NGC 5068 (540 kpc projected, 730 kpc in RV) (Karachentsev et al. 2017)

Alternative prototype(s): NGC 3109 association: adjacent to Local Group, membership: NGC 3109, Sextans A, Sextans B – too large on sky (van den Bergh 1999; Tully et al. 2006)

1.11.3 Galaxy group

Only compact and "fossil" groups are included due to practicality considerations, as neither of these types is vastly larger than a galaxy (Hickson 1993), whereas nearby galaxy groups cover too much of the sky to practically observe.

Compact galaxy group: Stephan's Quintet [503]

Type description: Very dense group of galaxies; projected diameter $\lesssim$ 100 kpc; $\gtrsim$ 4 members not vastly fainter than brightest member

Type references: Hickson (1982, 1993, 1997)

Stephan's Quintet *is sidereal source*

Stephan's Quintet also known as: HCG 92

Reason for selection of Stephan's Quintet: First discovered; most studied, most cited of Hickson (1982), most cited group of Hickson et al. (1989) catalog; implicit prototype

Notes on Stephan's Quintet: NGC 7320 is a foreground galaxy; group is triplet that interacted with displaced NGC 7320c, now interacting with "intruder" NGC 7318b

Works where Stephan's Quintet referred to as prototype: Duc et al. (2018)

Works relating Stephan's Quintet to type: Moles et al. (1997); Sulentic et al. (2001); Duc et al. (2018)

General works about Stephan's Quintet: O'Sullivan et al. (2009); Sulentic et al. (2001); Appleton et al. (2013); Guillard et al. (2012); van der Hulst & Rots (1981)

Fossil group: NGC 6482 [504]

Type description: Elliptical galaxy formed from all large galaxies in group merging; very bright in X-rays; no neighbor galaxies of comparable brightness

Caveats about type: La Barbera et al. (2009) questions existence of distinct class: fossil groups fall on elliptical galaxy relations

Type references: Ponman et al. (1994); Jones et al. (2003)

NGC 6482 *is sidereal source*

Reason for selection of NGC 6482: Nearest example; characteristics fit Ponman et al. (1994) definition

General works about NGC 6482: Buote (2017); Khosroshahi et al. (2004)

Galaxy interaction shock: Stephan's Quintet [503]

Type description: Galaxy- to group-scale shock created by galaxy collisions; can accelerate cosmic ray electrons and emit radio, sources of line emission and X-rays; distinct from cluster radio relics from galaxy cluster mergers

Type references: Condon et al. (1993); Sulentic et al. (2001); Rich et al. (2011)

Stephan's Quintet *is sidereal source*

Reason for selection of Stephan's Quintet: Well-studied in multiple bands; region being observed already

Notes on Stephan's Quintet: Detected in continuum radio, molecular emission, infrared lines, X-rays; probably triggered by NGC 7318b infall into group

Works relating Stephan's Quintet to type: van der Hulst & Rots (1981); Sulentic et al. (2001); O'Sullivan et al. (2009); Guillard et al. (2012); Appleton et al. (2013)

General works about Stephan's Quintet: Sulentic et al. (2001); Duc et al. (2018); Moles et al. (1997)

Alternative prototype(s): Taffy galaxies (UGC 12914/12915): radio-emitting bridge in stripped ISM post-merger (Condon et al. 1993)

1.11.4 Galaxy clusters

A very simple galaxy cluster classification scheme is used, based on relative symmetry and richness (compare with the more elaborate systems in Bahcall 1977).

Regular galaxy cluster: Fornax Cluster [505]

Type description: Radially symmetric, relaxed galaxy cluster with compact core; almost all large galaxies are early-type
Type references: Abell (1965); Bahcall (1977)

Fornax Cluster *is sidereal source*
Reason for selection of Fornax Cluster: Nearest example; well-studied
Caveats about selection of Fornax Cluster: An infalling subcluster of dwarf galaxies is present (Drinkwater et al. 2001)
Notes on Fornax Cluster: Core radius: 250 kpc; will be the target of a targeted MeerKAT program
General works about Fornax Cluster: Ferguson (1989); Jordán et al. (2007)
Relationships between Fornax Cluster and other Exotica Catalog objects: Contains within projected sky region: NGC 1365 [461]

Alternative prototype(s): Coma Cluster: example of R type cluster in Abell et al. (1989), accreting NGC 4839 group (Colless & Dunn 1996)

Irregular galaxy cluster: Virgo Cluster [506]

Type description: Asymmetrical, diffuse, subgroups still coalescing from progenitor cluster capture; spiral galaxies among population
Type references: Abell (1965); Bahcall (1977)

Virgo Cluster *is sidereal source*
Reason for selection of Virgo Cluster: Nearest example; extremely well-studied; many members covered in I17 and in Exotica catalog
Caveats about selection of Virgo Cluster: Abell et al. (1989) classifies Virgo as intermediate RI because galaxies are mostly early-type
Notes on Virgo Cluster: Contains two large subclusters, associated with M87 and M49, possibly a smaller one associated with M86; core radius: 600 kpc Jordán et al. (2007)
General works about Virgo Cluster: Côté et al. (2004); Mei et al. (2007); Binggeli et al. (1985a); Ferrarese et al. (2012)
Relationships between Virgo Cluster and other Exotica Catalog objects: Contains within projected sky region: HVGC-1 [672], M59 [392], M59-UCD3 [626], M85-HCC 1 [611], M86 tULX-1 [763], M91 [456], M99 [419], RZ 2109 ULX [313], UGC 7321 [466], VCC 1287 [441], XRT 000519 [760]
Relationships between Virgo Cluster and objects in I17: Contains within projected sky region: NGC 4489, NGC 4486B, M87, M49, NGC 4478, M86, NGC 4473, NGC 4660, M60, M87, M84, NGC 4564, NGC 4551, NGC 4387, NGC 4239, NGC 4458

Alternative prototype(s): Hercules Cluster: example of I type cluster in Abell et al. (1989)

Poor galaxy cluster: Fornax Cluster [505]

Type description: Low total mass, relatively few bright galaxies (in Abell (1958): few within two magnitudes of third brightest member); more common
Type references: Price et al. (1991); White et al. (1999)

Fornax Cluster *is sidereal source*
Reason for selection of Fornax Cluster: Nearby example; well-studied; compact
Notes on Fornax Cluster: Richness class 0 (c.f. richness class 1 for Virgo; Girardi et al. 1995); total mass: $\sim 7 \times 10^{13}$ $M_\odot$ (Jordán et al. 2007); will be the target of a targeted MeerKAT program
General works about Fornax Cluster: Ferguson (1989); Jordán et al. (2007)
Relationships between Fornax Cluster and other Exotica Catalog objects: Contains within projected sky region: NGC 1365 [461]

Rich galaxy cluster: Coma Cluster [507]

Type description: High total mass, many bright galaxies (in Abell (1958): many within two magnitudes of third brightest

member); rare
Type references: Abell et al. (1989)

Coma Cluster *is sidereal source*
Coma Cluster also known as: Abell 1656
Reason for selection of Coma Cluster: Nearest example; extremely well-studied
Notes on Coma Cluster: Richness class 2 (Abell et al. 1989); virial mass: 3×10^{15} $M_\odot$ (Kubo et al. 2007)
General works about Coma Cluster: Carter et al. (2008); Colless & Dunn (1996)
Relationships between Coma Cluster and other Exotica Catalog objects: Contains within projected sky region: Coma C [512]

Cool core cluster: Perseus Cluster [508]

Type description: Cluster where some intracluster gas has cooled and condensed into star-forming cool filaments (cooling flows) in cluster center; catastrophic cooling prevented by heating
Type references: Fabian (1994); Edge (2001); Peterson & Fabian (2006); Hudson et al. (2010)

Perseus Cluster *is sidereal source*
Perseus Cluster also known as: Abell 429
Reason for selection of Perseus Cluster: Well-studied; NGC 1275 elsewhere in catalog; nearest strong example
Notes on Perseus Cluster: NGC 1275 is the center of the Perseus Cluster; cooling flow is "residual", with radiative cooling mostly balanced from energy input possibly from AGN
Works where Perseus Cluster referred to as prototype: Edge (2001); Nagai et al. (2019)
Works relating Perseus Cluster to type: Holtzman et al. (1992); Lim et al. (2008)
General works about Perseus Cluster: Fabian et al. (2000, 2006, 2011); Sanders & Fabian (2007)
Relationships between Perseus Cluster and other Exotica Catalog objects: Contains within projected sky region: NGC 1265 [481], NGC 1275 minihalo [513], NGC 1277 [402], NGC 1277* [689]

Merging cluster: Bullet Cluster [509]

Type references: Ricker & Sarazin (2001)

Bullet Cluster *is sidereal source*
Bullet Cluster also known as: 1E 0657-558
Reason for selection of Bullet Cluster: Explicit prototype of merger bow shock; famous example
Notes on Bullet Cluster: Host a merger shock; post head-on collision, ICM left between clusters, displaced from stars and dark matter; $z = 0.30$
Works relating Bullet Cluster to type: Clowe et al. (2006)
General works about Bullet Cluster: Wik et al. (2014); Tucker et al. (1998); Markevitch et al. (2002); Clowe et al. (2006)
Relationships between Bullet Cluster and other Exotica Catalog objects: Gravitationally lenses: J 06587-5558 [692]

1.11.5 Protoclusters

Protocluster: SSA22 [510]

Type description: Galaxy overdensity that will evolve into galaxy cluster; generally refers to those at $z \gtrsim$ 1–2; not yet coalesced into virialized halo; no X-ray emitting ICM
Type references: Chiang et al. (2013); Overzier (2016)

SSA22 *is sidereal source*
Reason for selection of SSA22: One of first recognized; well-studied; SSA22a-LAB01 already being observed
Notes on SSA22: $z = 3.09$
Works relating SSA22 to type: Steidel et al. (1998); Tamura et al. (2009)
Relationships between SSA22 and other Exotica Catalog objects: Contains within projected sky region: SSA22a-LAB01 [389]

1.11.6 Intracluster medium

1.11.6.1 Thermal intracluster medium structures

Cold front: Abell 3667 [511]

Type description: Relatively sharp discontinuity between cold, dense and hot, rarefied gas in ICM
Caveats about type: Two types of cold front: remnant cool core (formed from subcluster merger) and sloshing cool core (Owers et al. 2009)
Type references: Markevitch & Vikhlinin (2007); Owers et al. (2009)

Abell 3667 *is sidereal source*
Reason for selection of Abell 3667: One of first recognized; cluster well-studied; appears obvious to eye in X-ray images (as in Figure 3 of Markevitch & Vikhlinin 2007)
Notes on Abell 3667: Has undergone merger
General works about Abell 3667: Owers et al. (2009); Vikhlinin et al. (2001)

Shock front: Bullet Cluster [509]

Type description: Cluster-scale; formed at site of colliding gas flows, with density and temperature discontinuity; strong shocks known to form from collision of ICMs in merging clusters, weak shocks known to be launched by AGNs in clusters; visible in X-rays
Relationship with other types: Can appear as radio relics
Type references: McNamara et al. (2005); Markevitch & Vikhlinin (2007); Gu et al. (2019)

Bullet Cluster *is sidereal source*
Reason for selection of Bullet Cluster: Explicit prototype of merger shock; shock is very prominent in X-ray images; cluster well-studied; Bullet Cluster elsewhere in catalog
Works where Bullet Cluster referred to as prototype: Markevitch et al. (2002)
General works about Bullet Cluster: Wik et al. (2014); Tucker et al. (1998); Clowe et al. (2006)
Relationships between Bullet Cluster and other Exotica Catalog objects: Gravitationally lenses: J 06587-5558 [692]

X-ray cavities: Perseus Cluster [508]

Type description: Large ($\sim$ 30 kpc, a few examples $\gtrsim$ 100 kpc) hot bubbles in ICM blown by AGN in central galaxy; appear as holes in images
Relationship with other types: Interior to AGN-driven shock fronts; can be site of lobes in radio galaxies
Type references: McNamara et al. (2005); McNamara & Nulsen (2007); Wise et al. (2007); Fabian et al. (2011)

Perseus Cluster *is sidereal source*
Reason for selection of Perseus Cluster: Well-studied example; NGC 1275 and Perseus Cluster elsewhere in catalog
Notes on Perseus Cluster: Contains a pair of inner bubbles (present-day radio lobes), a pair of "ghost" relic bubbles further out, evidence for more distant ancient bubbles
Works relating Perseus Cluster to type: Fabian et al. (2000, 2006); Sanders & Fabian (2007); Fabian et al. (2011)
General works about Perseus Cluster: Edge (2001); Lim et al. (2008); Nagai et al. (2019); Holtzman et al. (1992); Sanders & Fabian (2007)
Relationships between Perseus Cluster and other Exotica Catalog objects: Contains within projected sky region: NGC 1265 [481], NGC 1275 minihalo [513], NGC 1277 [402], NGC 1277* [689]

1.11.6.2 Nonthermal intracluster medium structures

Giant radio halo: Coma C [512]

Type description: Cluster-scale ($\sim$ 1 Mpc), round radio structures, found in centers of galaxy clusters; low surface brightness; correlated with X-ray emitting ICM; thought to be related to energy release in cluster mergers
Type references: Ferrari et al. (2008); Feretti et al. (2012); Brunetti & Jones (2014); van Weeren et al. (2019)

Coma C *is sidereal source*
Reason for selection of Coma C: Explicit prototype; nearby, brightest; well-studied example; Coma Cluster elsewhere in catalog

Works where Coma C referred to as prototype: Giovannini et al. (1991); Burns et al. (1992); Thierbach et al. (2003); Ferrari et al. (2008); Feretti et al. (2012); Brunetti & Jones (2014); van Weeren et al. (2019)
Works relating Coma C to type: Kim et al. (1990); Thierbach et al. (2003)
General works about Coma C: Ackermann et al. (2016b)
Relationships between Coma C and other Exotica Catalog objects: Within the sky region occupied by: Coma Cluster [507]; Adjacent on sky to (sharing parent object with): 1253+275 [514]

Radio minihalo: NGC 1275 minihalo [513]

Type description: Smaller than clusters (∼ 100–300 kpc, about size of cool core); round and centered on central radio galaxy, but can have complex substructure; can be surface brightness; emission from cosmic ray electrons somehow energized or delivered by AGN; found in cool core clusters
Relationship with other types: Distinct from radio lobes of radio galaxy (larger, mixed with ICM)
Type references: Ferrari et al. (2008); Feretti et al. (2012); Brunetti & Jones (2014); Giacintucci et al. (2017); van Weeren et al. (2019)

NGC 1275 minihalo *is sidereal source*
Reason for selection of NGC 1275 minihalo: Explict prototype; nearby; well-studied example; Perseus Cluster elsewhere in catalog
Works where NGC 1275 minihalo referred to as prototype: Feretti et al. (2012); van Weeren et al. (2019)
Works relating NGC 1275 minihalo to type: Burns et al. (1992); Gendron-Marsolais et al. (2017)
Relationships between NGC 1275 minihalo and other Exotica Catalog objects: Within the sky region occupied by: Perseus Cluster [508]

Radio relic: 1253+275 [514]

Type description: Long (∼ 1 Mpc), thin radio arc at edge of galaxy cluster; believed to be associated with cluster interaction shock; very polarized in radio
Relationship with other types: Not related to relic AGNs
Type references: Ferrari et al. (2008); Feretti et al. (2012); Brunetti & Jones (2014); van Weeren et al. (2019)

1253+275 *is sidereal source*
Reason for selection of 1253+275: Explicit prototype; nearby; Coma Cluster elsewhere in catalog
Notes on 1253+275: On edge of Coma Cluster, 70′ from center
Works where 1253+275 referred to as prototype: Feretti et al. (2012)
Works relating 1253+275 to type: Giovannini et al. (1991)
Relationships between 1253+275 and other Exotica Catalog objects: Within the sky region occupied by: Coma Cluster [507]; Adjacent on sky to (sharing parent object with): Coma C [512]

1.12 Large-scale structure

A phylum that covers structures that are forming from the density perturbations present in the early Universe. They are extremely diffuse and either unbound or only loosely bound. Examples include superclusters, voids, and "Great walls" of galaxies. Because of the accelerating expansion of the Universe, most of these structures will never have a chance to coalesce but will instead be dispersed. There are a few exceptions, however, like the Shapley Supercluster.

The intergalactic medium (IGM) is placed under this phylum.

Because these objects are so diffuse, they are mostly either too large to observe as a whole (like voids), or ubiquitous and found along every sightline (like Lyman α forest clouds). The included "attractor" and "repeller" points are not physical objects, but instead indicate local sinks and sources in the peculiar velocity of galaxies. They do roughly correspond to a dense group of clusters and a void, respectively (Hoffman et al. 2017), and may draw the attention of ETIs as special places.

1.12.1 Intergalactic medium

Giant HI ring: Leo Ring [515]

Type description: Ring of atomic hydrogen surrounding galaxy group; possibly source of (relatively) primordial IGM accreting onto galaxies

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Leo Ring *is sidereal source*
Reason for selection of Leo Ring: Nearby; famous example
Caveats about selection of Leo Ring: Leo Ring may be a collisional ring galaxy: (Rood & Williams 1985; Michel-Dansac et al. 2010), still unclear origin; probably polluted with metals ($Z \sim 0.1$ $Z_{\odot}$) from Leo Group metal if primordial (Bot et al. 2009; Rosenberg et al. 2014)
Notes on Leo Ring: Diameter: 200 kpc; no sign of distributed starlight, but pockets of star formation exist (Thilker et al. 2009; Watkins et al. 2014)
Works relating Leo Ring to type: Schneider et al. (1983); Schneider (1985); Thilker et al. (2009); Rosenberg et al. (2014)
General works about Leo Ring: Watkins et al. (2014)

1.12.2 Gravitational basin

Attractor: Laniakea (Great) attractor [516]

Type description: Location of sink drawing in galaxies, as seen in their peculiar velocities, due to galaxy cluster overdensity
Type references: Kocevski & Ebeling (2006); Tully et al. (2014); Hoffman et al. (2017)

Laniakea (Great) attractor *is sidereal source*
Reason for selection of Laniakea (Great) attractor: Historically known example
Notes on Laniakea (Great) attractor: Some distance from the classical position of Great Attractor, which Tully et al. (2014) associate it with; Great Attractor reported in Dressler et al. (1987); Lynden-Bell et al. (1988), roughly coincident with Norma Cluster (Kraan-Korteweg et al. 1996), now considered to be combination of real overdensity, observational artifacts, and larger flows to further and larger Shapley Supercluster and possibly Sloan Great Wall (Kocevski & Ebeling 2006; Feindt et al. 2013)
Works relating Laniakea (Great) attractor to type: Tully et al. (2014); Hoffman et al. (2017)

Alternative prototype(s): Shapley Attractor: more powerful and larger attractor, subsuming Laniakea – more distant (Kocevski & Ebeling 2006; Hoffman et al. 2017)

Repeller: Dipole repeller [517]

Type description: Location from which galaxies seem to stream, as if pushed away, in peculiar velocities, due to galaxy cluster underdensity
Type references: Hoffman et al. (2017)

Dipole repeller *is sidereal source*
Reason for selection of Dipole repeller: Main known example
Works relating Dipole repeller to type: Kocevski & Ebeling (2006); Hoffman et al. (2017)

1.13 Technology

The final phylum of physical objects in the current version of the catalog, covering spaceborne objects built by intelligence. They are built intentionally, although this may have to include technology built by other technology that itself lacks intelligence or sentience. These intentions can widely vary, but can include processing of matter, energy, and information.

All the examples are anthropogenic at present. SETI aims to find or constrain technology that does not originate on Earth, as observed through its technosignatures.

Which active satellites are available for observation will depend on new launches and re-entries. Although we list some major classes of satellite, the selection of most of the individual sources will be opportunistic.

1.13.1 Space station

Space station: International Space Station [518]

International Space Station *is Solar System source*
Reason for selection of International Space Station: Only example currently in orbit (early 2020)

1.13.2 Satellite

1.13.3 Spacecraft

Space probe: *Voyager 1* [525]

Type description: Interplanetary vehicle for space exploration; downlink generally by modulated narrowband radio transmissions

Voyager 1 *is Solar System source*
Reason for selection of Voyager 1*:* Already observed by Breakthrough Listen
Notes on Voyager 1*:* Most distant functioning probe launched by human

Relationship to SETI: Narrowband radio transmissions similar to expected ETI technosignature; possibly size of ETI probe

Solar sail: *LightSail 2* [526]

LightSail 2 *is Solar System source*

Relationship to SETI: Analogous to interstellar light sail like Breakthrough Starshot, if it stopped in the target system?

Radar calibration target: Lincoln Calibration Sphere-1 [527]

Type description: Passive satellite used to test radar observations

Lincoln Calibration Sphere-1 *is Solar System source*
Notes on Lincoln Calibration Sphere-1: Satellite is unpowered aluminum sphere
General works about Lincoln Calibration Sphere-1: Hall et al. (2007)

Relationship to SETI: In near-infrared I-band photometry, satellite's reflectivity is mainly specular (Hall et al. 2007) – specular reflectivity has been proposed as a technosignature of Solar System artifacts by Lacki (2019), although more in the context of flat planes instead of spheres.

1.13.4 Space debris

Derelict satellite: Vanguard I [528]

Vanguard I *is Solar System source*
Reason for selection of Vanguard I: Oldest orbiting satellite

Dipole clump: 1963-014G [530]

Type description: Aggregate of copper needles deployed into Earth orbit as part of US West Ford project, a passive debris belt to relay radio communications; most needles have fallen too Earth
Type references: Project (1961); Lovell et al. (1962); Mandeville & Perrin (2006)

1963-014G *is Solar System source*
Reason for selection of 1963-014G: Largest RCS

NaK coolant drop: Cosmos 860 coolant (1976-103G) [531]

Type description: Sphere of frozen NaK liquid alloy used as coolant in Soviet nuclear-powered satellites
Type references: Matney et al. (2019)

Cosmos 860 coolant (1976-103G) *is Solar System source*
Reason for selection of Cosmos 860 coolant (1976-103G): Largest RCS of known drops
Notes on Cosmos 860 coolant (1976-103G): RCS: 180 cm^2
General works about Cosmos 860 coolant (1976-103G): Hall et al. (2007)

Relationship to SETI: In near-infrared I-band photometry, the NaK droplets observed by Hall et al. (2007) are specularly reflecting – specular reflectivity has been proposed as a technosignature of Solar System artifacts by Lacki (2019), although more in the context of flat planes instead of spheres.

Car: Tesla Roadster [532]

Tesla Roadster *is Solar System source*

Notes on Tesla Roadster: Automobile launched on interplanetary orbit; broadcast radio transmissions on launch, but should be defunct now; tracked with optical telescopes upon departure

Works relating Tesla Roadster to type: Rein et al. (2018)

Relationships between Tesla Roadster and other Exotica Catalog objects: Orbital primary: Sun [150]

Relationship to SETI: Vehicle size may be comparable to ETI probe; optical spectrum possibly a technosignature?

1.14 Reference point

A final "phylum" that includes targets that are not physical objects but may have observer-relative significance.

1.14.1 Solar System-relative reference points

Solar antipoint: Solar antipoint [533]

Solar antipoint *is Solar System source*

Notes on Solar antipoint: Location on sky directly opposite of Sun; includes Earth-Sun L_2 point; apparent site of gegenschein, which is the glow of interplanetary dust that backscatters light directly towards the Sun

Relationships between Solar antipoint and other Exotica Catalog objects: Opposite point on sky from: Sun [150]

Relationship to SETI: ETIs near Solar antipoint may target Earth for broadcast, as it transits Sun from their perspective (Shostak 2004; c.f. the much broader "Earth Transit Zone" in Heller & Pudritz 2016; Sheikh et al. 2020)

Earth-moon stable Lagrange point: Earth-Moon L_5 [534]

Type description: Location 60° ahead or behind Moon in orbit around Earth; objects located in its vicinity can maintain relatively stable orbits near this location (Trojan objects)

Earth-Moon L_5 *is Solar System source*

Relationship to SETI: Has been the target of SETA searches

Earth-sun stable Lagrange point: Earth-Sun L_4 [535]

Type description: Location 60° ahead or behind Earth in orbit around Sun; Earth Trojans are objects located in this vicinity which can maintain relatively stable orbits near this location

Earth-Sun L_4 *is Solar System source*

Reason for selection of Earth-Sun L_4: Known to have Earth Trojan, in catalog

Relationships between Earth-Sun L_4 and other Exotica Catalog objects: Orbital primary: Sun [150]

Relationship to SETI: Proposed to be location for ETI probes by Benford (2019)

1.14.2 Galactic-relative reference points

Galactic anticenter: Galactic anticenter [536]

Type description: Point on sidereal sphere directly opposite the Galactic center as viewed from Earth

Notes on type: To the vantage point of an observer in the anticenter direction, Earth appears to be aligned over the Galactic center

Galactic anticenter *is sidereal source*

Relationship to SETI: Benford et al. (2010) proposed that at each point in the Galactic disk, the Center-antiCenter line of sight defines a preferred axis. Thus ETIs with limited power would most likely transmit towards the Center and back out the anticenter in reply. When observing the anticenter, we would be sensitive to the Center-directed transmissions of ETIs further out than us.

2. Superlatives

Superlatives include the objects with the most extreme fundamental properties known. Sometimes, however, the Superlatives are merely "apparent" instead of "true" because observational biases prevent us from detecting more extreme objects are common. We give our judgement for whether the listed Superlative is "true" or not using the following rankings:

- ✓– The value listed is likely to be among the most extreme for that type of object;
- ✕ – The value is likely to be greatly superseded with further discoveries, with more extreme objects undetectable with current capabilities;
- R – The value is likely on the tail of a distribution, but there are likely to be Rare objects that are significantly more extreme;
- ? – It is unclear whether the Superlative is true or apparent;
- S – The value is likely to be among the most extreme in the Solar System, but not necessarily beyond it;
- M – The value is likely to be among the most extreme in the Milky Way, but not necessarily beyond it; and
- L – The value is likely to be among the most extreme in the Local Group but not necessarily beyond it.

These may be combined – for example, an evaluation of "✓?" indicates the Superlative is probably "true" but there is reason to suspect a population of more extreme objects could exist, or "✕/S" indicates that the Superlative is among the most extreme in the Solar System but far more extreme objects are thought to exist beyond it.

2.1 Minor bodies

2.1.1 All minor bodies

α_G^V **(darkest):** $0.027^{+0.006}_{-0.007}$ – 1173 Anchises [537]

Description: Lowest geometric albedo in V-band
Evaluation as true superlative: ✓ – Very near minimum albedo of zero. Conceivably, a much smaller log α_G^V is possible, though, but there is no reason to expect it.

1173 Anchises *is Solar System source*
Reason for selection of 1173 Anchises: Described explicitly as having extreme albedo
Works where 1173 Anchises referred to as superlative: Horner et al. (2012b)
References for data on 1173 Anchises: Horner et al. (2012b)
Relationships between 1173 Anchises and other Exotica Catalog objects: Orbital primary: Sun [150]

α_G^V **(brightest):** $0.76^{+0.18}_{0.45}$–$0.88^{+0.15}_{-0.06}$ – (55636) 2002 TX_{300} [538]

Description: Highest geometric albedo in V-band
Evaluation as true superlative: ✓ – Near maximum albedo of one for Lambertian reflectors. However, albedos above one are possible for backscattering objects or specular reflection.

(55636) 2002 TX_{300} *is Solar System source*
Reason for selection of (55636) 2002 TX_{300}: Consistently among largest values we found in literature
References for data on (55636) 2002 TX_{300}: Elliot et al. (2010); Vilenius et al. (2018)
Relationships between (55636) 2002 TX_{300} and other Exotica Catalog objects: Orbital primary: Sun [150]

M_{host} **(smallest):** 8^{+7}_{-3} M_J – Cha 110913-773444 [539]

Description: Isolated host (star or substellar object) with smallest mass
Status as true superlative unknown

Cha 110913-773444 *is sidereal source*
Cha 110913-773444 designation in Simbad: Cha J110913-773444

Reason for selection of Cha 110913-773444: Implicit superlative as first planetary-mass disk host discovered
Notes on Cha 110913-773444: Minor bodies detected as infrared excess from circumstellar disk
Works where Cha 110913-773444 referred to as superlative: Luhman et al. (2005)
References for data on Cha 110913-773444: Luhman et al. (2005)

Alternative superlative object(s): [AKC2006] 17: sub-brown dwarf with mid-IR excess, ~ 6 M_J (Allers et al. 2006)

2.1.2 Interplanetary minor bodies

a **(closest):** 0.5553 ± 0.0002 AU – 2019 LF_6 [540]

Description: Smallest semimajor axis in orbit around Sun
Evaluation as true superlative: ✕/S? – This being a recent discovery suggests other similar bodies exist, some of which may be more superlative. Hypothetical Vulcanoid populations would be much closer to Sun (e.g., Evans & Tabachnik 1999). Minor bodies with tighter orbits exist with near certainty in more compact planetary systems, like those found around many red dwarfs.

2019 LF_6 *is Solar System source*
Reason for selection of 2019 LF_6: Explicit superlative
Works where 2019 LF_6 referred to as superlative: de la Fuente Marcos & de la Fuente Marcos (2019)
References for data on 2019 LF_6: de la Fuente Marcos & de la Fuente Marcos (2019)
Relationships between 2019 LF_6 and other Exotica Catalog objects: Orbital primary: Sun [150]

Alternative superlative object(s): 2020 AV_2: 0.55542 ± 0.00010 AU, confidence intervals overlap (de la Fuente Marcos & de la Fuente Marcos 2020a)

Q **(closest):** 0.65377 ± 0.00012 AU – 2020 AV_2 [016]

Description: Smallest aphelion in orbit around Sun
Evaluation as true superlative: ✕/S? – This being a recent discovery suggests other similar bodies exist, some of which may be more superlative. Hypothetical Vulcanoid populations would be much closer to Sun (e.g., Evans & Tabachnik 1999). Minor bodies with tighter orbits exist with near certainty in more compact planetary systems, like those found around many red dwarfs.

2020 AV_2 *is Solar System source*
Reason for selection of 2020 AV_2: Explicit superlative; only Vatira, an aphelion-based criterion
Works where 2020 AV_2 referred to as superlative: Greenstreet (2020); de la Fuente Marcos & de la Fuente Marcos (2020a)
References for data on 2020 AV_2: Jet Propulsion Laboratory (2020a)
Other works on 2020 AV_2: Greenstreet (2020)
Relationships between 2020 AV_2 and other Exotica Catalog objects: Orbital primary: Sun [150]

q **(furthest):** 80.40 ± 0.09 AU – 2012 VP_{113} [541]; 65.2 ± 0.2 AU – 541132 Leleākūhonua [052]

Description: Largest perihelion in orbit around Sun
Evaluation as true superlative: ✕ – The Oort Cloud is much further out, and should include objects in not-too eccentric orbits (Duncan et al. 1987), but its population is undetectable.

2012 VP_{113} *is Solar System source*
Reason for selection of 2012 VP_{113}: Explicit superlative
Caveats about selection of 2012 VP_{113}: Brown (2020): "likely" dwarf planet
Works where 2012 VP_{113} referred to as superlative: Trujillo & Sheppard (2014)
References for data on 2012 VP_{113}: Jet Propulsion Laboratory (2020a)
Relationships between 2012 VP_{113} and other Exotica Catalog objects: Orbital primary: Sun [150]

541132 Leleākūhonua *is Solar System source*
541132 Leleākūhonua also known as: 2015 TG_{387}
Reason for selection of 541132 Leleākūhonua: Third largest perihelion, highest after Sedna and 2012 VP_{113}, a superlative remarked upon in Sheppard et al. (2019)
Works where 541132 Leleākūhonua referred to as superlative: Sheppard et al. (2019)

References for data on 541132 Leleākūhonua: Jet Propulsion Laboratory (2020a)
Other works on 541132 Leleākūhonua: Sheppard et al. (2019)
Relationships between 541132 Leleākūhonua and other Exotica Catalog objects: Orbital primary: Sun [150]

2.1.3 Minor satellites

R (largest): 210 ± 7 km – Proteus [542]

Description: Largest radius without achieving hydrostatic equilibrium
Evaluation as true superlative: ✓ – Expected to be near maximum size of nonspherical body, possibly in a transitional regime (Croft 1992).

Proteus *is Solar System source*
Reason for selection of Proteus: Explicit superlative for size of non-spherical body
Works where Proteus referred to as superlative: Croft (1992)
References for data on Proteus: Jet Propulsion Laboratory (2020d)
Relationships between Proteus and other Exotica Catalog objects: Orbital primary: Neptune [065]

a **(closest, planet host):** 9,376 km – Phobos [053]

Description: Smallest semi-major axis around dwarf planet or planetary host
Evaluation as true superlative: ✗/S – Direct inspection of Solar System. Analogous bodies in exosystems undetectable, but there is no reason a small moon could not orbit a planet closer as long as it has internal strength or the planet is smaller.

Phobos *is Solar System source*
Caveats about selection of Phobos: Moons of small minor bodies orbit much closer
References for data on Phobos: Jet Propulsion Laboratory (2020b)
Other works on Phobos: Rosenblatt (2011)
Relationships between Phobos and other Exotica Catalog objects: Orbital primary: Mars [082]

a **(furthest):** 50 Gm – Neso [543]

Description: Largest semi-major axis around host
Evaluation as true superlative: S – Direct inspection of Solar System, combined with Neptune's Hill sphere being the largest of the major planets. Analogous bodies in exosystems undetectable.

Neso *is Solar System source*
References for data on Neso: Jet Propulsion Laboratory (2020b)
Relationships between Neso and other Exotica Catalog objects: Orbital primary: Neptune [065]

$a/\mathbf{R}_p$ **(smallest):** 1.79 – Metis [544]

Description: Smallest ratio of semimajor axis to host's radius, for dwarf planet or planet hosts
Evaluation as true superlative: ✓ – Near tidal disruption limit

Metis *is Solar System source*
Caveats about selection of Metis: We did not consider satellites of small minor bodies
References for data on Metis: Jet Propulsion Laboratory (2020b,c)
Relationships between Metis and other Exotica Catalog objects: Orbital primary: Jupiter [113]

2.1.4 Planetary rings

$\mathbf{M}_{\mathrm{host}}$ **(smallest):** $\sim 8 \times 10^{-7}$ $M_\oplus$ – 2060 Chiron [039]

Description: Ring system with smallest mass host
Status as true superlative unknown

2060 Chiron *is Solar System source*
Notes on 2060 Chiron: Mass estimated from diameter (166 km; JPL SBDB) and a density of 2 $\mathrm{g\,cm^{-3}}$
Works where 2060 Chiron referred to as superlative: Ortiz et al. (2015)

References for data on 2060 Chiron: Jet Propulsion Laboratory (2020a)
Other works on 2060 Chiron: Jewitt (2009); Ortiz et al. (2015); Hartmann et al. (1990)
Relationships between 2060 Chiron and other Exotica Catalog objects: Orbital primary: Sun [150]

M_{host} (largest): $\sim$ 14–26 M_J – 1SWASP J140752.03-394415.1 b [545]

Description: Ring system with largest mass host
Status as true superlative unknown

1SWASP J140752.03-394415.1 b *is sidereal source*
1SWASP J140752.03-394415.1 b designation in Simbad: 1SWASP J140752.03-394415.1
Reason for selection of 1SWASP J140752.03-394415.1 b: Only Super-Jovian/brown dwarf known to host rings
Works where 1SWASP J140752.03-394415.1 b referred to as superlative: Kenworthy et al. (2015)
References for data on 1SWASP J140752.03-394415.1 b: Kenworthy et al. (2015)
Other works on 1SWASP J140752.03-394415.1 b: Mamajek et al. (2012)

R (smallest): 324 km – 2060 Chiron [039]

Description: Ring with smallest radius around host
Status as true superlative unknown

2060 Chiron *is Solar System source*
Works where 2060 Chiron referred to as superlative: Ortiz et al. (2015)
References for data on 2060 Chiron: Ortiz et al. (2015)
Other works on 2060 Chiron: Jet Propulsion Laboratory (2020a); Jewitt (2009); Ortiz et al. (2015); Hartmann et al. (1990)
Relationships between 2060 Chiron and other Exotica Catalog objects: Orbital primary: Sun [150]

R (largest): $\sim$ 27 Gm – 1SWASP J140752.03-394415.1 b [545]

Description: Ring with largest radius around host
Status as true superlative unknown

1SWASP J140752.03-394415.1 b *is sidereal source*
1SWASP J140752.03-394415.1 b designation in Simbad: 1SWASP J140752.03-394415.1
Works where 1SWASP J140752.03-394415.1 b referred to as superlative: Mamajek et al. (2012)
References for data on 1SWASP J140752.03-394415.1 b: Mamajek et al. (2012)
Other works on 1SWASP J140752.03-394415.1 b: Kenworthy et al. (2015)

Alternative superlative object(s): Saturn Phoebe ring: 16 Gm (Hamilton et al. 2015)

2.2 Solid planetoid

2.2.1 All solid planetoids

M (smallest): 6.3×10^{-6} $M_\oplus$ – Mimas [546]

Description: Smallest mass
Evaluation as true superlative: ✓ – Expected to be near minimum limit for spherical solid planetoid (although note caveat about Methone).

Mimas *is Solar System source*
Caveats about selection of Mimas: Methone appears to have achieved hydrostatic equilibrium, but is much too small to be a solid planetoid
References for data on Mimas: Jet Propulsion Laboratory (2020d)
Other works on Mimas: Jet Propulsion Laboratory (2020d)
Relationships between Mimas and other Exotica Catalog objects: Orbital primary: Saturn [064]

R (smallest): 198.2 ± 0.3 km – Mimas [546]

Description: Smallest radius

Evaluation as true superlative: ✓ – Expected to be near minimum limit for spherical solid planetoid (although note caveat about Methone) – compare with Proteus.

Mimas *is Solar System source*
Caveats about selection of Mimas: Methone appears to have achieved hydrostatic equilibrium, but is much too small to be a solid planetoid
References for data on Mimas: Jet Propulsion Laboratory (2020d)
Other works on Mimas: Jet Propulsion Laboratory (2020d)
Relationships between Mimas and other Exotica Catalog objects: Orbital primary: Saturn [064]

α_G **(darkest):** < 0.10 – Iapetus [547]; 0.09 – 1 Ceres [095]

Description: Lowest geometric albedo
Evaluation as true superlative: ✓ – Very near minimum albedo of zero. Conceivably, a much smaller $\log \alpha_G$ is possible, though, but there is no reason to expect it.

Iapetus *is Solar System source*
Notes on Iapetus: Iapetus' low albedo applies only to its dark regions
References for data on Iapetus: Howett et al. (2010)
Other works on Iapetus: Denk et al. (2010); Porco et al. (2005); Jet Propulsion Laboratory (2020d)
Relationships between Iapetus and other Exotica Catalog objects: Orbital primary: Saturn [064]

1 Ceres *is Solar System source*
References for data on 1 Ceres: Jet Propulsion Laboratory (2020a)
Other works on 1 Ceres: Ruesch et al. (2016); Jet Propulsion Laboratory (2020a); Russell et al. (2016); Park et al. (2016)
Relationships between 1 Ceres and other Exotica Catalog objects: Orbital primary: Sun [150]

Alternative superlative object(s): 120347 Salacia: $\alpha_V = 0.044$, may be dwarf planet with 450 km diameter (Vilenius et al. 2012)

α_G **(brightest):** 1.3 – Enceladus [107]

Description: Largest geometric albedo
Evaluation as true superlative: ✓ – Combination of nearly pure white surface with backscattering suggests nearly ideal conditions for Superlative.

Enceladus *is Solar System source*
References for data on Enceladus: Jet Propulsion Laboratory (2020d)
Other works on Enceladus: Spencer & Nimmo (2013); Porco et al. (2006)
Relationships between Enceladus and other Exotica Catalog objects: Orbital primary: Saturn [064]

2.2.2 Major satellites

M (largest): 0.0248 $M_\oplus$ – Ganymede [106]

Description: Largest mass
Evaluation as true superlative: S – Direct inspection of Solar System. Ganymede is larger than dwarf planets that may still be discovered and thus their satellites, although hypothetically additional major planets may exist with even larger moons. Satellites of exoplanets as of yet generally undetectable.

Ganymede *is Solar System source*
References for data on Ganymede: Jet Propulsion Laboratory (2020d)
Other works on Ganymede: Barr & Canup (2010); Jet Propulsion Laboratory (2020d)
Relationships between Ganymede and other Exotica Catalog objects: Orbital primary: Jupiter [113]

R (largest): 2,631 km – Ganymede [106]

Description: Largest mean radius
Evaluation as true superlative: S – Direct inspection of Solar System. Ganymede is larger than dwarf planets that may still

be discovered and thus their satellites, although hypothetically additional major planets may exist with even larger moons. Satellites of exoplanets as of yet generally undetectable.

Ganymede *is Solar System source*

References for data on Ganymede: Jet Propulsion Laboratory (2020d)

Other works on Ganymede: Barr & Canup (2010); Jet Propulsion Laboratory (2020d)

Relationships between Ganymede and other Exotica Catalog objects: Orbital primary: Jupiter [113]

ρ **(lowest):** 0.973 $\mathrm{g\,cm^{-3}}$ – Tethys [548]

Description: Lowest mean density

Evaluation as true superlative: ✓? / S – Direct inspection of Solar System. Bulk density of ices are constraints on density for large bodies with limited porosity. Satellites of exoplanets as of yet generally undetectable.

Tethys *is Solar System source*

References for data on Tethys: Jet Propulsion Laboratory (2020d)

Relationships between Tethys and other Exotica Catalog objects: Orbital primary: Saturn [064]

ρ **(highest):** 3.528 $\mathrm{g\,cm^{-3}}$ – Io [108]

Description: Largest mean density

Evaluation as true superlative: ✗?/S – Direct inspection of Solar System. Any undetected Solar System major satellites are in the far outer Solar System, likely to be icy and lower in density. Satellites of exoplanets as of yet generally undetectable. Presumably a denser body with a stripped mantle like Mercury or a larger body like Earth around a giant planet could form or be captured as a moon.

Io *is Solar System source*

References for data on Io: Jet Propulsion Laboratory (2020d)

Other works on Io: Khurana et al. (2011); Veeder et al. (2012); McEwen et al. (2000)

Relationships between Io and other Exotica Catalog objects: Orbital primary: Jupiter [113]

$\mathbf{M_{moon}/M_{host}}$ **(smallest):** 6.60×10^{-8} $\mathrm{M_\oplus}$ – Mimas [546]

Description: Smallest ratio of satellite mass and host mass

Evaluation as true superlative: ✗/S – Direct inspection of Solar System. Mimas is near the expected minimum size of a major satellite, and it is unlikely any planets larger than Saturn remain to be discovered in the Solar System. Satellites of exoplanets as of yet generally undetectable. Presumably a body like Mimas could be a moon around a super-Jovian planet.

Mimas *is Solar System source*

References for data on Mimas: Jet Propulsion Laboratory (2020d)

Other works on Mimas: Jet Propulsion Laboratory (2020d)

Relationships between Mimas and other Exotica Catalog objects: Orbital primary: Saturn [064]

$\mathbf{M_{moon}/M_{host}}$ **(largest):** 0.122 – Charon [549]

Description: Smallest ratio of satellite mass and host mass

Evaluation as true superlative: ✗?/S – Direct inspection of Solar System. Satellites of exoplanets as of yet generally undetectable, but there are plausibly nearly-equal ratio systems (binary dwarf planets) around other suns.

Charon *is Solar System source*

References for data on Charon: Stern et al. (2018)

Other works on Charon: Stern et al. (2018)

Relationships between Charon and other Exotica Catalog objects: Orbital primary: 134340 Pluto [097]

$\mathbf{M_{moon}/M_{host}}$ **(largest, planet):** 0.0123 – Moon [101]

Description: Smallest ratio of satellite mass and major planet host mass

Evaluation as true superlative: ✗?/S – Direct inspection of Solar System. Satellites of exoplanets as of yet generally undetectable, but there are plausibly nearly-equal ratio systems (binary planets) around other suns.

Moon *is Solar System source*

References for data on Moon: Jet Propulsion Laboratory (2020d)
Other works on Moon: Asphaug (2014); Haruyama et al. (2009); Hiesinger et al. (2003); Stevenson (1987)

Relationship to SETI: The Moon is suggested to hold meteorites from Earth recording ancient "alternate" life (Davies & Lineweaver 2005); could be location of probes or artifacts (Arkhipov & Graham 1996; Davies & Wagner 2013); reflects Earth's radio emission (Moonbounce), allowing study of its radio technosignatures (McKinley et al. 2013; DeMarines et al. 2019)

a **(closest):** 19.6 Mm – Charon [549]

Description: Smallest semimajor axis in orbit around host
Evaluation as true superlative: ✕/S? – Direct inspection of Solar System. It is possible that an unknown dwarf planet has a closer major satellite, or that an unknown close-in satellite exists, however. Satellites of exoplanets as of yet generally undetectable, but likewise a smaller dwarf planet in another solar system could easily have a closer moon.

Charon *is Solar System source*
References for data on Charon: Stern et al. (2018)
Other works on Charon: Stern et al. (2018)
Relationships between Charon and other Exotica Catalog objects: Orbital primary: 134340 Pluto [097]

Alternative superlative object(s): Vanth (Orcus I) – a: 9,000 km, R: 220 km (may be major satellite) (Sickafoose et al. 2019); Ilmarë (Varda I) – a: 4,800 km, R: 160 km (may be major satellite) (Grundy et al. 2015)

a **(closest, planet):** 129.9 Mm – Miranda [550]

Description: Smallest semimajor axis in orbit around major planet host
Evaluation as true superlative: ✕/S – Direct inspection of Solar System. Satellites of exoplanets as of yet generally undetectable, but major satellites could easily exist closer to planets, especially smaller host planets.

Miranda *is Solar System source*
References for data on Miranda: Jet Propulsion Laboratory (2020d)
Relationships between Miranda and other Exotica Catalog objects: Orbital primary: Uranus [676]

a **(furthest):** 3.56 Gm – Iapetus [547]

Description: Largest semimajor axis in orbit around major planet host
Evaluation as true superlative: ✕?/S – Direct inspection of Solar System. Satellites of exoplanets as of yet generally undetectable, but major satellites could probably exist much further out into the Hill sphere (which can also be larger than Saturn's), perhaps through three-body capture mechanisms.

Iapetus *is Solar System source*
References for data on Iapetus: Jet Propulsion Laboratory (2020d)
Other works on Iapetus: Denk et al. (2010); Porco et al. (2005); Howett et al. (2010)
Relationships between Iapetus and other Exotica Catalog objects: Orbital primary: Saturn [064]

2.2.3 Dwarf planets

M (smallest): 0.000157 $M_\oplus$ – 1 Ceres [095]

Description: Smallest mass
Evaluation as true superlative: ? – The dwarf planet status of many TNOs is uncertain, but many of them could be less massive than Ceres.

1 Ceres *is Solar System source*
References for data on 1 Ceres: Jet Propulsion Laboratory (2020a)
Other works on 1 Ceres: Ruesch et al. (2016); Jet Propulsion Laboratory (2020a); Russell et al. (2016); Park et al. (2016)
Relationships between 1 Ceres and other Exotica Catalog objects: Orbital primary: Sun [150]

Alternative superlative object(s): 10 Hygiea – M: 1.4×10^{-5} $M_\oplus$, possible dwarf planet (Vernazza et al. 2020)

M (largest): 0.0028 $M_\oplus$ – 136199 Eris [096]

Description: Largest mass

Evaluation as true superlative: S – Direct inspection of Solar System. Dwarf planets of exosystems as of yet generally undetectable.

136199 Eris *is Solar System source*
Reason for selection of 136199 Eris: Explicit superlative
Works where 136199 Eris referred to as superlative: Brown & Schaller (2007)
References for data on 136199 Eris: Brown & Schaller (2007)
Other works on 136199 Eris: Brown & Schaller (2007); Brown et al. (2005a); Sicardy et al. (2011); Jet Propulsion Laboratory (2020a)
Relationships between 136199 Eris and other Exotica Catalog objects: Orbital primary: Sun [150]

R (smallest): 469.7 km – 1 Ceres [095]

Description: Smallest geometric mean radius
Evaluation as true superlative: ? – The dwarf planet status of many TNOs is uncertain, but many of them could be less massive than Ceres.

1 Ceres *is Solar System source*
References for data on 1 Ceres: Russell et al. (2016)
Other works on 1 Ceres: Ruesch et al. (2016); Jet Propulsion Laboratory (2020a); Russell et al. (2016); Park et al. (2016)
Relationships between 1 Ceres and other Exotica Catalog objects: Orbital primary: Sun [150]

Alternative superlative object(s): 10 Hygiea – R: 217 km, possible dwarf planet (Vernazza et al. 2020); many possible dwarf planets in outer Solar System (Brown 2020)

R (largest): 1,188 km – 134340 Pluto [097]

Description: Largest geometric mean radius
Evaluation as true superlative: S – Direct inspection of Solar System. Dwarf planets of exosystems as of yet generally undetectable.

134340 Pluto *is Solar System source*
References for data on 134340 Pluto: Stern et al. (2018)
Other works on 134340 Pluto: Stern et al. (2018); Nimmo et al. (2016); McKinnon et al. (2016)
Relationships between 134340 Pluto and other Exotica Catalog objects: Orbital primary: Sun [150]; Hosts (is primary of): Charon [549]

a **(closest):** 2.768 AU – 1 Ceres [095]

Description: Smallest semimajor axis in orbit around Sun
Evaluation as true superlative: ✕/S – Direct inspection of Solar System. 10 Hygiea is has a larger semimajor axis, 3.1424 AU. Dwarf planets of exosystems as of yet generally undetectable, but there is no reason they could not exist closer, particularly in more compact planetary systems around red dwarfs.

1 Ceres *is Solar System source*
References for data on 1 Ceres: Jet Propulsion Laboratory (2020a)
Other works on 1 Ceres: Ruesch et al. (2016); Jet Propulsion Laboratory (2020a); Russell et al. (2016); Park et al. (2016)
Relationships between 1 Ceres and other Exotica Catalog objects: Orbital primary: Sun [150]

a **(furthest):** 67.86 AU – 136199 Eris [096]; 484.4 AU – 90377 Sedna [098]

Description: Largest semimajor axis in orbit around Sun
Evaluation as true superlative: ✕ – The detection of Sedna implies dwarf planets exist in the Oort Cloud. The Oort Cloud should include objects in not-too eccentric orbits (Duncan et al. 1987) which are undetectable (Brown et al. 2004).

136199 Eris *is Solar System source*
Notes on 136199 Eris: Eris has the largest *a* of the IAU-recognized dwarf planets, but Sedna is very likely to be a dwarf planet too
References for data on 136199 Eris: Jet Propulsion Laboratory (2020a)

Other works on 136199 Eris: Brown & Schaller (2007); Brown et al. (2005a); Sicardy et al. (2011)
Relationships between 136199 Eris and other Exotica Catalog objects: Orbital primary: Sun [150]

90377 Sedna *is Solar System source*
References for data on 90377 Sedna: Jet Propulsion Laboratory (2020a)
Other works on 90377 Sedna: Morbidelli & Levison (2004); Brown et al. (2004); Pál et al. (2012)
Relationships between 90377 Sedna and other Exotica Catalog objects: Orbital primary: Sun [150]

2.2.4 Solid major planets

M (smallest): 0.020 ± 0.002 $\mathrm{M}_\oplus$ – PSR 1257+12 A [094]

Description: Smallest major planet mass
Evaluation as true superlative: ✕ – Much smaller major planets are possible, as demonstrated by existence of smaller dwarf planets and major satellites. The limits of current exoplanet detection techniques is the likeliest explanation for the failure to detect smaller bodies.

PSR 1257+12 A *is sidereal source*
PSR 1257+12 A designation in Simbad: PSR B1257+12
PSR 1257+12 A also known as: PSR 1257+12 b
Reason for selection of PSR 1257+12 A: Third smallest mass listed in exoplanet.eu; smallest that is not debris or disintegrating
Works where PSR 1257+12 A referred to as superlative: Schneider et al. (2011)
References for data on PSR 1257+12 A: Konacki & Wolszczan (2003)
Other works on PSR 1257+12 A: Konacki & Wolszczan (2003); Wolszczan & Frail (1992)

M (smallest, non-pulsar host): $0.066^{+0.059}_{-0.037}$–(0.187 ± 0.050) $\mathrm{M}_\oplus$ – Kepler 138 b [551]

Description: Smallest major planet mass with non-pulsar host
Evaluation as true superlative: ✕ – Much smaller major planets are possible, as demonstrated by existence of smaller dwarf planets and major satellites. The limits of current exoplanet detection techniques is the likeliest explanation for the failure to detect smaller bodies.

Kepler 138 b *is sidereal source*
Kepler 138 b designation in Simbad: Kepler 138
Reason for selection of Kepler 138 b: Next smallest mass after PSR 1257+12 A in exoplanet.eu
Works where Kepler 138 b referred to as superlative: Schneider et al. (2011)
References for data on Kepler 138 b: Almenara et al. (2018)

R (smallest): $0.303^{+0.053}_{-0.073}$ $\mathrm{R}_\oplus$ – Kepler 37 b [552]

Description: Smallest major planet radius
Evaluation as true superlative: ✕ – Much smaller major planets are possible, as demonstrated by existence of smaller dwarf planets and major satellites. The limits of current exoplanet detection techniques is the likeliest explanation for the failure to detect smaller bodies.

Kepler 37 b *is sidereal source*
Kepler 37 b designation in Simbad: Kepler 37
Reason for selection of Kepler 37 b: Implicit superlative (first smaller than Mercury); fifth smallest radius in exoplanet.eu: first three are minor bodies, fourth is Kepler 391 b (radius in error, actually 2.5 ± 0.3 $\mathrm{R}_\oplus$; Jofré et al. 2020
Works where Kepler 37 b referred to as superlative: Barclay et al. (2013)
References for data on Kepler 37 b: Barclay et al. (2013)

ρ (densest): 12.65 ± 2.49 $\mathrm{g\,cm^{-3}}$ – Kepler 107 c [553]

Description: Solid planet with the greatest density
Evaluation as true superlative: ✓ – Should be limited by bulk density of solid matter, which is relatively incompressible.

Kepler 107 c *is sidereal source*
Kepler 107 c designation in Simbad: Kepler 107

Reason for selection of Kepler 107 c: Implicit superlative
Works where Kepler 107 c referred to as superlative: Toledo-Padrón et al. (2020)
References for data on Kepler 107 c: Bonomo et al. (2019)

Alternative superlative object(s): K2-38 b: nearly as dense with $11.0^{+4.1}_{-2.8}$ g cm^{-3} (Toledo-Padrón et al. 2020)

α_G **(brightest):** 0.65 – Venus [085]

Description: Highest geometric albedo
Evaluation as true superlative: ✗?/S – Direct inspection of Solar System. Hypothetically an undiscovered icy major planet in the outer Solar System could be even more reflective, as demonstrated by Enceladus. Likewise, Encleadus demonstrates higher albedos are possible for exoplanets.

Venus *is Solar System source*
Reason for selection of Venus: Highest value we found
References for data on Venus: Jet Propulsion Laboratory (2020c)
Other works on Venus: Solomatov & Moresi (1996); Way et al. (2016); Kasting (1988); Nimmo & McKenzie (1998)
Relationships between Venus and other Exotica Catalog objects: Orbital primary: Sun [150]

Alternative superlative object(s): Kepler 10 b – α_G: $0.58^{+}0.08_{-0.35}$ (Esteves et al. 2015)

t **(oldest):** 11.0 ± 0.8 Gyr – Kepler 444 [083]; $\sim$ 12–13 Gyr – 82 Eri [554]

Description: Oldest major planets
Evaluation as true superlative: ✓ – Approaches maximum age allowed by time since Big Bang. Hypothetically, in terms of age of Universe at planet formation, much more Superlative planets could exist, although it would be hard to identify them without much more precise ages. Behroozi & Peeples (2015) finds a non-zero terrestrial planet formation rate at $z \sim 8$, although only at $z \lesssim 4$ did it reach its current rate. Mashian & Loeb (2016) speculates that carbon planets could have formed at very high redshift around intrinsically carbon-enhanced metal poor stars.

Kepler 444 *is sidereal source*
Reason for selection of Kepler 444: Explicit superlative
Works where Kepler 444 referred to as superlative: Campante et al. (2015)
References for data on Kepler 444: Buldgen et al. (2019)
Other works on Kepler 444: Mills & Fabrycky (2017); Campante et al. (2015)

82 Eri *is sidereal source*
82 Eri also known as: e Eri; HD 20794; HR 1008
Reason for selection of 82 Eri: High age we found in literature
References for data on 82 Eri: Bernkopf et al. (2012)
82 Eri in I17

P (shortest): 4.25 hr – KOI 1843.03 [555]

Description: Shortest orbital period around host star
Evaluation as true superlative: ? – May depend on host star type.

KOI 1843.03 *is sidereal source*
KOI 1843.03 designation in Simbad: KOI-1843.03
Reason for selection of KOI 1843.03: Explicit superlative
Works where KOI 1843.03 referred to as superlative: Ofir & Dreizler (2013); Rappaport et al. (2013)
References for data on KOI 1843.03: Ofir & Dreizler (2013); Rappaport et al. (2013)

N_{planet} **(most):** 7 – TRAPPIST-1 [091]

Description: Most confirmed (terrestrial) planets in system
Status as true superlative unknown

TRAPPIST-1 *is sidereal source*
Reason for selection of TRAPPIST-1: Highest value we found; well-studied system

References for data on TRAPPIST-1: Gillon et al. (2017)
Other works on TRAPPIST-1: Gillon et al. (2017); Gonzales et al. (2019); Pinchuk et al. (2019); Luger et al. (2017)

Alternative superlative object(s): Kepler 90 (=KOI 351): has seven planets, but some are giant planets (Schmitt et al. 2014); Sun: has eight planets, but only four terrestrial planets

M_{host} (smallest, star): 0.086 ± 0.008 $M_\odot$ – TRAPPIST-1 [091]

Description: Lowest mass host star
Evaluation as true superlative: ✓ – Host star near hydrogen burning limit. Planets around much smaller brown dwarfs are likely to exist, however.

TRAPPIST-1 *is sidereal source*
Reason for selection of TRAPPIST-1: Lowest value we found; approaching lower limit to stellar mass; well-studied system
Notes on TRAPPIST-1: Also among the coldest and faintest host stars known
References for data on TRAPPIST-1: Gonzales et al. (2019)
Other works on TRAPPIST-1: Gillon et al. (2017); Pinchuk et al. (2019); Luger et al. (2017)

2.3 Giant planets

R (biggest, < 1 M_J): $22.9^{+1.1}_{-0.8}$ $R_\oplus$ – HAT-P-67 b [556]

Description: Largest radius giant planet with mass less than 1 Jupiter
Evaluation as true superlative: ✓? – Reasons for inflation unclear, but excessive radii would need an energy source; also larger planets should be easier to detect with the transit method

HAT-P-67 b *is sidereal source*
HAT-P-67 b designation in Simbad: HAT-P-67
Reason for selection of HAT-P-67 b: Radius largest in exoplanet.eu for planet with mass less than 9 M_J; large radius commented upon in Zhou et al. (2017)
Notes on HAT-P-67 b: We wished to exclude planets with masses near ~ 10 M_J because these might be brown dwarfs; HAT-P-67 b has mass $0.34^{+0.25}_{-0.19}$ M_J
References for data on HAT-P-67 b: Zhou et al. (2017)

ρ (lowest): $0.034^{+0.069}_{-0.019}$ $\mathrm{g\,cm^{-3}}$ – Kepler 51 c [557]

Description: Lowest density giant planet
Evaluation as true superlative: ✓? – Reasons for inflation unclear, but excessive radii would need an energy source; also low density planets should be easier to detect with the transit method

Kepler 51 c *is sidereal source*
Kepler 51 c designation in Simbad: Kepler 51
Reason for selection of Kepler 51 c: Smallest value we found in literature (e.g., Piro & Vissapragada 2020)
References for data on Kepler 51 c: Libby-Roberts et al. (2020)

Alternative superlative object(s): Kepler 51 d – density: 0.038 ± 0.006 $\mathrm{g\,cm^{-3}}$ (Libby-Roberts et al. 2020); HAT-P-67 b: density: $0.052^{+0.039}_{-0.028}$ $\mathrm{g\,cm^{-3}}$ (Zhou et al. 2017)

T (hottest): $4{,}050 \pm 180$ K – KELT 9 b [558]

Description: Hottest (predicted) surface temperature
Status as true superlative unknown

KELT 9 b *is sidereal source*
KELT 9 b designation in Simbad: KELT-9
KELT 9 b also known as: HD 195689 b
Reason for selection of KELT 9 b: Explicit superlative
Works where KELT 9 b referred to as superlative: Gaudi et al. (2017)
References for data on KELT 9 b: Gaudi et al. (2017)
Other works on KELT 9 b: Gaudi et al. (2017)

α_G **(darkest):** 0.025–0.05 – TrES-2 b [559]

Description: Lowest geometric albedo
Evaluation as true superlative: ✓ – Very near minimum albedo of zero. Conceivably, a much smaller log α_G is possible, though, but there is no reason to expect it.

TrES-2 b *is sidereal source*
TrES-2 b designation in Simbad: TrES-2
TrES-2 b also known as: Kepler 1 b
Reason for selection of TrES-2 b: Explicit superlative; among lowest values we found in literature
Notes on TrES-2 b: Actual albedo may be somewhat lower depending on atmospheric heat redistribution
Works where TrES-2 b referred to as superlative: Kipping & Spiegel (2011)
References for data on TrES-2 b: Kipping & Spiegel (2011); Angerhausen et al. (2015); Esteves et al. (2015)

Alternative superlative object(s): WASP-104 b – α_G: 0.025 ± 0.007 (Močnik et al. 2018, which says TrES-2b is "at least as dark")

α_G **(brightest):** 0.52 – Jupiter [113]

Description: Highest geometric albedo
Status as true superlative unknown

Jupiter *is Solar System source*
Reason for selection of Jupiter: Highest value we found
References for data on Jupiter: Jet Propulsion Laboratory (2020c)
Other works on Jupiter: Bolton et al. (2017); Hubbard & Militzer (2016); Seiff et al. (1996)
Relationships between Jupiter and other Exotica Catalog objects: Hosts (is primary of): Amalthea [054], Himalia [056], Europa [104], Callisto [105], Ganymede [106], Io [108], Metis [544]; Orbital primary: Sun [150]

Alternative superlative object(s): Kepler 7 b – α_G: 0.32 ± 0.03 (Demory et al. 2011)

t **(youngest):** 2 Myr – V830 Tau b [560]

Description: Youngest giant planet (youngest host star)
Evaluation as true superlative: ✓ – Giant planet formation expected to take of order a few million years, so near minimum possible value

V830 Tau b *is sidereal source*
V830 Tau b designation in Simbad: V830 Tau
Reason for selection of V830 Tau b: Youngest we found in literature; youth remarked upon in Donati et al. (2016)
Notes on V830 Tau b: $M \sin i$: 0.77 M_J
References for data on V830 Tau b: Donati et al. (2016)

Alternative superlative object(s): CI Tau b – age: 2 Myr, $M \sin i$: 8.1 M_J (possibly not planet)

t **(oldest):** 11.2–12.7 Gyr – PSR B1620-26 (AB) b [124]

Description: Oldest giant planet
Evaluation as true superlative: ✓ – Approaches maximum age allowed by time since Big Bang. Hypothetically, in terms of age of Universe at planet formation, much more Superlative planets could exist, although they would be hard to identify them without much more precise ages. Behroozi & Peeples (2015) finds a non-zero Galactic terrestrial planet formation rate at $z \sim 2$, rising to its current rate at $z \sim 1$. M4 appears to be at least about a billion years older (formation at $z \sim 3$). A small fraction of the Universe's giant planets are expected to form as early as $z \sim 4$ in Behroozi & Peeples (2015).

PSR B1620-26 (AB) b *is sidereal source*
PSR B1620-26 (AB) b designation in Simbad: PSR B1620-26
Reason for selection of PSR B1620-26 (AB) b: Oldest we found in literature
Notes on PSR B1620-26 (AB) b: Age is estimated age of globular cluster M4 in which planet resides; pulsar planet but probably not original host. M4 age given as 12.7 Gyr Sigurdsson & Thorsett (2005), 11.6 ± 0.6 Gyr (white dwarf cooling Bedin et al.

2009), 12.50 ± 0.50 Gyr (horizontal branch Dotter et al. 2010), 11.2–11.3 Gyr (eclipsing binaries, most probable Kaluzny et al. 2013), 12.45 ± 0.7 Gyr (adopted for giant stars MacLean et al. 2018)

References for data on PSR B1620-26 (AB) b: Sigurdsson & Thorsett (2005)

Other works on PSR B1620-26 (AB) b: Sigurdsson & Thorsett (2005); Thorsett et al. (1999); Ford et al. (2000)

$M_{\rm host}$ (largest): 2.8 $M_\odot$ – κ And b [561]; 1.6–3.2 $M_\odot$ – o UMa b [562]

Description: Most massive host star

Evaluation as true superlative: ✕ – Below $\lesssim 3$ $M_\odot$, stellar host mass is correlated with protoplanetary disk mass (Andrews et al. 2013) and planetary system mass (Johnson et al. 2010; Ghezzi et al. 2018). More massive stars likely have massive protoplanetary disks and likely planets, but observational biases in our current planetary detection methods makes them hard to detect (Veras et al. 2020).

κ And b *is sidereal source*

κ And b designation in Simbad: kap And

Reason for selection of κ And b: Largest reliable value we found in literature

Caveats about selection of κ And b: Planet quite likely to be brown dwarf – estimate mass: 12.8^{+2}_{-1} M_J (Carson et al. 2013), 22^{+8}_{-9} M_J (Jones et al. 2016a), 13^{+12}_{-2} M_J (Currie et al. 2018)

References for data on κ And b: Currie et al. (2018)

Other works on κ And b: Currie et al. (2018)

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o UMa b *is sidereal source*

o UMa b designation in Simbad: omi UMa

Reason for selection of o UMa b: Explicit superlative; relatively massive star even in conservative estimates; likely planet-mass

Notes on o UMa b: $M_{\rm host}$: 3.09 ± 0.07 $M_\odot$ (Sato et al. 2012), 1.6 $M_\odot$ (Andreasen et al. 2017), 2.7 $M_\odot$ (Stock et al. 2018); $M \sin i$: 2.7–4.1 M_J

Works where o UMa b referred to as superlative: Veras et al. (2020)

References for data on o UMa b: Sato et al. (2012); Andreasen et al. (2017); Stock et al. (2018)

Alternative superlative object(s): ϵ Tau b: $M_{\rm host}$ – 2.7 ± 0.1 $M_\odot$ (Sato et al. 2007), 2.46 ± 0.07 $M_\odot$ (Arentoft et al. 2019), $M \sin i$: 7.6 ± 0.2 M_J (Sato et al. 2007); M51-ULS-1b – claimed planet around X-ray binary in M51, system mass ~ 10 $M_\odot$ assuming high-mass X-ray binary as supposed, compact object progenitor mass $\gtrsim 9$ $M_\odot$ – detection based on single claimed X-ray transit, with verification nearly impossible because of long orbital period (Di Stefano et al. 2020)

$L_{\rm host}$ (brightest): ~ 610 (500–730) $L_\odot$ – HD 208527 b [563]

Description: Host star with highest bolometric luminosity

Evaluation as true superlative: ✕ – Planets almost certainly exist around stars at the tip of the Asymptotic Giant Branch, and likely around massive supergiant stars (see $M_{\rm host}$, largest), but observational biases in our current planetary detection methods makes them hard to detect (c.f., Veras et al. 2020).

HD 208527 b *is sidereal source*

HD 208527 b designation in Simbad: HD 208527

Reason for selection of HD 208527 b: Highest value we found in literature

Caveats about selection of HD 208527 b: Planet may be brown dwarf – $M \sin i$: 9.9 ± 1.7 M_J (Lee et al. 2013)

References for data on HD 208527 b: Lee et al. (2013); Stassun et al. (2017); Gaia Collaboration et al. (2018b)

Alternative superlative object(s): Aldebaran b – $L_{\rm host}$: 440 $L_\odot$ (Heiter et al. 2015), $M \sin i = 6.5 \pm 0.5$ M_J planet claimed by Hatzes et al. (2015) but Reichert et al. (2019) disputes its existence; M51-ULS-1b – claimed planet around X-ray binary in M51, X-ray luminosity: $\sim 10^{39}$ erg s^{-1} ($\sim$ 300,000 $L_\odot$; variable) – detection based on single claimed X-ray transit, with verification nearly impossible because of long orbital period (Di Stefano et al. 2020)

$T_{\rm host}$ (hottest): $11{,}327^{+421}_{-44}$ K – κ And b [561]; $10{,}170 \pm 450$ K – KELT 9 b [558]

Description: Host star with highest effective temperature

Evaluation as true superlative: ✕ – Massive stars on main sequence can be much hotter, and they could be giant planet hosts (see $M_{\rm host}$, largest), but observational biases in our current planetary detection methods makes them hard to detect (c.f., Veras et al. 2020).

κ **And b** *is sidereal source*
κ And b designation in Simbad: kap And
Reason for selection of κ And b: Highest value we found in literature
Caveats about selection of κ And b: Planet quite likely to be brown dwarf – estimate mass: 12.8^{+2}_{-1} M_J (Carson et al. 2013), 22^{+8}_{-9} M_J (Jones et al. 2016b), 13^{+12}_{-2} M_J (Currie et al. 2018)
References for data on κ And b: Currie et al. (2018)
Other works on κ And b: Currie et al. (2018)

KELT 9 b *is sidereal source*
KELT 9 b designation in Simbad: KELT-9
KELT 9 b also known as: HD 195689 b
Reason for selection of KELT 9 b: Explicit superlative
Notes on KELT 9 b: Mass: 2.88 ± 0.84 M_J
Works where KELT 9 b referred to as superlative: Gaudi et al. (2017)
References for data on KELT 9 b: Gaudi et al. (2017)
Other works on KELT 9 b: Gaudi et al. (2017)

Alternative superlative object(s): M51-ULS-1b – claimed planet around X-ray binary in M51, X-ray temperature: 100 eV (10^6 K; as supersoft ultraluminous X-ray source, actual temperature may appear lower than it is due to inclination effects) – detection based on single claimed X-ray transit, with verification nearly impossible because of long orbital period (Di Stefano et al. 2020)

a (furthest): 2,500 AU – GJ 3483 B [564]

Description: Largest semimajor axis in orbit around host
Evaluation as true superlative: ✕ – Planets with even wider semimajor axes (in Oort cloud like orbits) probably possible via near-ejections in interstellar space, but they would be difficult to detect except by microlensing.

GJ 3483 B *is sidereal source*
GJ 3483 B designation in Simbad: WD 0806-661B
GJ 3483 B also known as: WD 806-661 B
Reason for selection of GJ 3483 B: Largest semimajor axis in exoplanet.eu with $M < 10$ M_J
Caveats about selection of GJ 3483 B: Rodriguez et al. (2011): likely formed through gravitational instability and thus better described as sub-brown dwarf
Notes on GJ 3483 B: Mass: ~ 6–10 M_J
Works where GJ 3483 B referred to as superlative: Schneider et al. (2011)
References for data on GJ 3483 B: Rodriguez et al. (2011)

a (furthest, $\lesssim 1$ M_J): 137 AU – HD 163269 b [565]

Description: Giant planet of mass $\lesssim 1$ M_J with largest semimajor axis in orbit around host
Evaluation as true superlative: ✕ – Planets with even wider semimajor axes (in Oort cloud like orbits) probably possible via near-ejections in interstellar space, but they would be difficult to detect except by microlensing.

HD 163269 b *is sidereal source*
HD 163269 b designation in Simbad: HD 163269
Reason for selection of HD 163269 b: Planet b is largest semimajor axis in exoplanet.eu with $M < 1$ M_J
Caveats about selection of HD 163269 b: van der Marel et al. (2019) questions existence of these planets; mass of planets varies in literature (see Mesa et al. 2019)
Notes on HD 163269 b: Planet existence inferred from gaps in protoplanetary disk; mass: ~ 0.3–1.3 M_J; planet c is further out but more massive – a: 260 AU, M: ~ 2 M_J (Pinte et al. 2018)
References for data on HD 163269 b: Isella et al. (2016); Teague et al. (2018)

2.4 Stars

2.4.1 Sub-brown dwarfs

T_{eff} (coldest): 225–260 K – WISE J085510.83-071442.5 [133]

Description: Coldest effective temperature
Evaluation as true superlative: ✕ – Limited by observational bias: older sub-brown dwarfs less luminous and harder to detect

WISE J085510.83-071442.5 *is sidereal source*
Reason for selection of WISE J085510.83-071442.5: Explicit superlative
Works where WISE J085510.83-071442.5 referred to as superlative: Luhman (2014)
References for data on WISE J085510.83-071442.5: Luhman (2014)
Other works on WISE J085510.83-071442.5: Leggett et al. (2017); Skemer et al. (2016); Luhman (2014)

2.4.2 Stars

M (largest): 265^{+80}_{-35}–315^{+60}_{-15} $M_\odot$ – R136 a1 [566]

Description: Highest mass star
Evaluation as true superlative: L – Constrained by direct observations of Milky Way and Magellanic Clouds. Historically, an empirical mass limit of ~ 150 $M_\odot$ has been proposed (Figer 2005), but R136 a1 exceeds it (Crowther et al. 2010). More massive stars conceivably could exist in more extreme clusters found outside Local Group. Supermassive stars $\gtrsim 10^3$ $M_\odot$, possibly formed through runaway stellar collisions, may exist (or existed in the early Universe) (e.g., Portegies Zwart et al. 2004; Denissenkov & Hartwick 2014); they would probably lose mass quickly and end up below ~ 150 $M_\odot$ (Yungelson et al. 2008).

R136 a1 *is sidereal source*
R136 a1 designation in Simbad: RMC 136a
Reason for selection of R136 a1: Highest mass we found in recent literature; high mass remarked upon; suggested to be one of most massive stars in Local Group in Crowther et al. (2010)
Works where R136 a1 referred to as superlative: Crowther et al. (2010)
References for data on R136 a1: Crowther et al. (2016)
Other works on R136 a1: Crowther et al. (2016)
Works on R136 a1's host: Pietrzyński et al. (2019)
Relationships between R136 a1 and other Exotica Catalog objects: Within the sky region occupied by: 30 Dor [619]; Adjacent on sky to (sharing parent object with): CAL 83 nebula [382], Melnick 34 [600], N159F [385], NS 1987A [592], OGLE LMC-CEP-4506 [702], PSR J0537-6910 [586], SN 1987A [375]
Relationships between R136 a1 and objects in I17: Within the sky region occupied by: LMC

L (faintest): 0.00013 $L_\odot$ – 2MASS J0523-1403 [142]

Description: Star with lowest bolometric luminosity
Evaluation as true superlative: ✓ – Near hydrogen-burning limit for main sequence (Dieterich et al. 2014)

2MASS J0523-1403 *is sidereal source*
2MASS J0523-1403 designation in Simbad: 2MASS J05233822-1403022
Reason for selection of 2MASS J0523-1403: Explicitly described as at or near bottom of main sequence
Works where 2MASS J0523-1403 referred to as superlative: Dieterich et al. (2014)
References for data on 2MASS J0523-1403: Dieterich et al. (2014)
Other works on 2MASS J0523-1403: Dieterich et al. (2014)

L (brightest): $8.7^{+2.0}_{-1.6} \times 10^6$ $L_\odot$ – R136 a1 [566]

Description: Star with highest (non-outbursting) luminosity
Evaluation as true superlative: L – Constrained by observations of Milky Way and Magellanic Clouds. Much brighter stars

would likely have to be more massive, especially given enormous radiation pressure (c.f., Yungelson et al. 2008; see entry for M, largest); also, brighter stars would be easier to detect.

R136 a1 *is sidereal source*
R136 a1 designation in Simbad: RMC 136a
Reason for selection of R136 a1: Highest luminosity we found in recent literature
References for data on R136 a1: Crowther et al. (2016)
Other works on R136 a1: Crowther et al. (2010, 2016)
Relationships between R136 a1 and other Exotica Catalog objects: Within the sky region occupied by: 30 Dor [619]; Adjacent on sky to (sharing parent object with): CAL 83 nebula [382], Melnick 34 [600], N159F [385], NS 1987A [592], OGLE LMC-CEP-4506 [702], PSR J0537-6910 [586], SN 1987A [375]
Relationships between R136 a1 and objects in I17: Within the sky region occupied by: LMC

Alternative superlative object(s): η Car – 4.6×10^6 $L_\odot$ (Mehner et al. 2019)

R (smallest): $0.084^{+0.014}_{-0.004}$ $R_\odot$ – EBLM J0555-57 Ab [567]; 0.086 ± 0.003 $R_\odot$ – 2MASS J0523-1403 [142]; 0.11 $R_\odot$ – Feige 34 [568]

Description: Star with smallest radius
Evaluation as true superlative: ✓ – Stars with small radii are necessarily at the "bottom" of the Hertzprung-Russel diagram, with the smallest luminosity for each temperature. The luminosity constraints are less severe for hotter stars (i.e., the "bottom left" corner of the HR diagram is most Superlative). EBLM J0555-57 Ab is near the hydrogen burning limit and thus near the bottom of the main sequence. Hot subdwarfs have similar radii to each other, and no further population of stars (as classified here) expected in between hot subdwarfs and white dwarfs. White dwarfs and other collapsed stars can be much smaller, however.

EBLM J0555-57 Ab *is sidereal source*
EBLM J0555-57 Ab designation in Simbad: EBLM J0555-57
Reason for selection of EBLM J0555-57 Ab: Explicit superlative; smallest radius we found in recent literature
Works where EBLM J0555-57 Ab referred to as superlative: von Boetticher et al. (2017)
References for data on EBLM J0555-57 Ab: von Boetticher et al. (2017)

2MASS J0523-1403 *is sidereal source*
2MASS J0523-1403 designation in Simbad: 2MASS J05233822-1403022
Reason for selection of 2MASS J0523-1403: Among smallest radius we found in recent literature, overlapping with EBLM J0555-57 Ab; explicitly described as having near-minimal radius for late dwarf stars
Works where 2MASS J0523-1403 referred to as superlative: Dieterich et al. (2014)
References for data on 2MASS J0523-1403: Dieterich et al. (2014)
Other works on 2MASS J0523-1403: Dieterich et al. (2014)

Feige 34 *is sidereal source*
Reason for selection of Feige 34: Smallest radius for hot star we inferred from literature
Notes on Feige 34: Luminosity: 158 $L_\odot$; effective temperature: 62,550 K; Stefan-Boltzmann law gives radius 0.107 $R_\odot$
References for data on Feige 34: La Palombara et al. (2019)
Other works on Feige 34: La Palombara et al. (2019)

R (largest): 5 – 13 AU – NML Cyg [569]; 8 ± 1 AU – UY Sct [570]

Description: Star with largest (mean) photospheric radius
Evaluation as true superlative: ✓ – Stars with large radius correspond to those with extremely high luminosity and low temperature, the cool hypergiants at the "top right" corner of the HR diagram. Mass loss is expected to prevent more massive (and potentially brighter) stars evolving into cool hypergiants, as empirically observed in the Humphreys & Davidson (1979) limit.

NML Cyg *is sidereal source*
Reason for selection of NML Cyg: Among largest radii we inferred from literature; explicitly noted to be among largest in Wing (2009)
Notes on NML Cyg: Zhang et al. (2012b) favors VLBI maser parallax distance $1.61^{+0.13}_{-0.11}$ kpc, luminosity $2.7 \pm 0.5 \times 10^5$ $(d/1.61\text{ kpc})^2 L_\odot$, effective temperature 2,500 AU, implying radius 13 AU; *Gaia* DR2 parallax implies distance of 660

pc, would give radius of 5 AU (Gaia Collaboration et al. 2018b); Xu et al. (2019) notes discrepancy between *Gaia* and VLBI maser parallaxes and favors the VLBI measurements

References for data on NML Cyg: Zhang et al. (2012b)

UY Sct *is sidereal source*

Reason for selection of UY Sct: Among largest radii we found in literature; largest in Wittkowski et al. (2017)

References for data on UY Sct: Wittkowski et al. (2017)

Alternative superlative object(s): VX Sgr – suggested by Wing (2009) to be largest/latest type with $R > 9$ AU, Xu et al. (2018) estimated radius: 5.2–7.2 AU; VY CMa – suggested by Wing (2009) to be among largest, Wittkowski et al. (2017) estimated radius: 6.6 ± 0.5 AU

ρ **(densest):** $\sim 530\ \mathrm{g\,cm^{-3}}$ – Feige 34 [568]

Description: Star with the largest mean density

Evaluation as true superlative: ✓ – All main sequence stars are much less dense. Feige 34 is a hot subdwarf, and no further population of stars (as classified here) expected in between hot subdwarfs and white dwarfs. White dwarfs and other collapsed stars are generally much more dense.

Feige 34 *is sidereal source*

Reason for selection of Feige 34: Superlative small radius combined with moderate subdwarf mass

Notes on Feige 34: Density calculated under assumption of $\mathrm{M} = 0.5\ \mathrm{M_\odot}$

References for data on Feige 34: La Palombara et al. (2019)

Other works on Feige 34: La Palombara et al. (2019)

Alternative superlative object(s): EBLM J0555-57 Ab: explicit superlative, 188 $\mathrm{g\,cm^{-3}}$(von Boetticher et al. 2017) – still much smaller than hot subdwarf densities

T **(coldest):** $2{,}074 \pm 21$ K – 2MASS J0523-1403 [142]

Description: Star with lowest effective temperature (Dieterich et al. 2014)

Evaluation as true superlative: ✓ – Near hydrogen-burning limit for main sequence, expected to be coolest stars.

2MASS J0523-1403 *is sidereal source*

2MASS J0523-1403 designation in Simbad: 2MASS J05233822-1403022

Reason for selection of 2MASS J0523-1403: Explicitly described as at or near bottom of main sequence

Works where 2MASS J0523-1403 referred to as superlative: Dieterich et al. (2014)

References for data on 2MASS J0523-1403: Dieterich et al. (2014)

Other works on 2MASS J0523-1403: Dieterich et al. (2014)

T **(hottest):** 210,000 K – WR 102 [200]

Description: Star with highest effective temperature

Evaluation as true superlative: ✓ – No theoretical reason to expect much hotter stars and no particular observational bias against them so far as we know.

WR 102 *is sidereal source*

Reason for selection of WR 102: Highest value we found in literature

References for data on WR 102: Tramper et al. (2015)

Other works on WR 102: Tramper et al. (2015)

t **(oldest):** 12–14 Gyr – HD 140283 [213]

Description: Star with greatest age as observed

Evaluation as true superlative: ✓ – Approaches maximum age allowed by time since Big Bang. Hypothetically, in terms of age of Universe at stellar birth, much more Superlative stars could exist, although it might be hard to identify them without much more precise ages unless they were clearly Population III (c.f., Bromm 2013). The earliest stars are expected to form only tens of Myr after the Big Bang ($z \sim 65$ according to Naoz et al. 2006). These very earliest stars have generally thought to be biased towards high masses and thus long since destroyed, but low mass Population III stars may have formed under some conditions (Greif et al. 2011; Stacy & Bromm 2014), perhaps found towards the Galactic Center or in dwarf galaxies (Ishiyama et al. 2016).

HD 140283 *is sidereal source*
Reason for selection of HD 140283: Explicit superlative; *Gaia* benchmark star that is well-studied
Notes on HD 140283: Literature ages: 14.5 ± 0.3 Gyr (Bond et al. 2013), 14.3 ± 0.4 Gyr (VandenBerg et al. 2014), (12.2 ± 0.6)–$(13.7$–$0.7)$ Gyr (Creevey et al. 2015); > 12.0 Gyr (Sahlholdt et al. 2019)
Works where HD 140283 referred to as superlative: Bond et al. (2013)
References for data on HD 140283: Bond et al. (2013)
Other works on HD 140283: Creevey et al. (2015); Bond et al. (2013); Heiter et al. (2015)

[Fe/H] (poorest): < -7.1 – SMSS J0313-6708 [571]

Description: Star with lowest iron abundance
Evaluation as true superlative: ✕ ? – Population III stars forming shortly after the Big Bang should have zero iron abundance (Bromm 2013). The existence of carbon in this star implies it is not Population III, and it likely has some iron. However, there is speculation that these metal-poorest stars are low mass Population III stars that have been polluted by accretion from the ISM (Komiya et al. 2015), particularly carbon-enhanced metal poor stars like SMSS J0313-6708 (Johnson 2015). The very earliest stars have generally thought to be biased towards high masses and thus long since destroyed, but low mass Population III stars may have formed under some conditions (Greif et al. 2011; Stacy & Bromm 2014), perhaps found towards the Galactic Center or in dwarf galaxies (Ishiyama et al. 2016).

SMSS J0313-6708 *is sidereal source*
SMSS J0313-6708 designation in Simbad: SMSS J031300.36-670839.3
Reason for selection of SMSS J0313-6708: Lowest iron abundance we found in literature
References for data on SMSS J0313-6708: Keller et al. (2014)

[Fe/H] (richest): ~ 0.5 – 14 Her [572]

Description: Star with highest iron abundance
Evaluation as true superlative: ? – Reported values of very high metallicity tend to be inconsistent between papers. Hopkins (2014) speculates that stars that are majority metal by mass exist, although they would be very rare.

14 Her *is sidereal source*
14 Her also known as: HD 145675
Reason for selection of 14 Her: Consistently high-ranked among metallicity catalogs and studies of super metal rich stars
Notes on 14 Her: [Fe/H]: 0.49 (highest of super metal rich stars studied in Feltzing & Gonzalez 2001), 0.45 (fifth highest in Taylor 2006), 0.18–0.63 (average: 0.42, Soubiran et al. 2016), 0.49 (third highest of 951 in CATSUP; Hinkel et al. 2017), 0.33 (highest in Caffau et al. 2019); A(C): 8.84 (three-way tie for highest in Caffau et al. 2019); Gonzalez et al. (1999) explicitly notes its high metallicity
References for data on 14 Her: Feltzing & Gonzalez (2001); Taylor (2006); Soubiran et al. (2016); Hinkel et al. (2017); Caffau et al. (2019)
14 Her in I17

Alternative superlative object(s): NE1-1 002 – in Galactic nucleus, [Fe/H]: 0.90 (Do et al. 2015), > 0.60 (Do et al. 2018); PASTEL 2016 lists many measurements of [Fe/H] $\gg 1$, with a maximum value of 2.4 for the Ap star HD 187474 (from Kearsley & Wegner 1978), but these generally do not seem to be replicated, and are mostly from older works

[C/H] (lowest): < -4.3 – SDSS J102915+172927 [573]

Description: Star with lowest carbon abundance
Evaluation as true superlative: ✕ – Population III stars forming shortly after the Big Bang should have zero iron abundance (Bromm 2013). The existence of iron and other metals in this star implies it is not Population III, and it likely has some carbon. However, there is speculation that these metal-poorest stars are low mass Population III stars that have been polluted by accretion from the ISM (Komiya et al. 2015). The very earliest stars have generally thought to be biased towards high masses and thus long since destroyed, but low mass Population III stars may have formed under some conditions (Greif et al. 2011; Stacy & Bromm 2014), perhaps found towards the Galactic Center or in dwarf galaxies (Ishiyama et al. 2016).

SDSS J102915+172927 *is sidereal source*

SDSS J102915+172927 designation in Simbad: SDSS J102915.14+172927.9

Reason for selection of SDSS J102915+172927: Lowest value we found in literature; noted to be extreme in Caffau et al. (2011)

References for data on SDSS J102915+172927: Caffau et al. (2011)

v **(fastest):** $23{,}923 \pm 8{,}840$ km s^{-1} – S4711 [574]

Description: Highest velocity relative to host galaxy attained by star

Evaluation as true superlative: ✕ – Relativistic velocities possible even closer to supermassive black holes, especially large ones. Tidal disruption events may involve even faster stars. Faint stars near Sgr A* that may venture closer are undetectable as of yet.

S4711 *is sidereal source*

Reason for selection of S4711: Stars in orbit around Sgr A* achieve much higher speeds than known hypervelocity stars; explicit superlative of these

Notes on S4711: Orbital velocity: 24,000 km s^{-1} (pericenter), 1,480 km s^{-1} ($r = a$), 91 km s^{-1} (apocenter), derived from Peißker et al. (2020)

Works where S4711 referred to as superlative: Peissker et al. (2020); Peißker et al. (2020)

References for data on S4711: Peißker et al. (2020)

Other works on S4711: Peißker et al. (2020)

Relationships between S4711 and other Exotica Catalog objects: Within the sky region occupied by: Central Cluster [343]; Orbital primary: Sgr A* [471]; Adjacent on sky to (sharing parent object with): G2 [669], IRS 16E [604], IRS 16C [668], S0-2 [667]

Alternative superlative object(s): S0-16 – orbital velocity: 12,510 km s^{-1} (pericenter), 1,440 km s^{-1} ($r = a$), 160 km s^{-1} (apocenter) (derived from Chu et al. 2018); S0-2 – orbital velocity: 7,890 km s^{-1} (pericenter), 1,880 km s^{-1} ($r = a$), 450 km s^{-1} (apocenter) (derived from Chu et al. 2018); S0-138 – orbital velocity: 5,480 km s^{-1} (pericenter), 1,770 km s^{-1} ($r = a$), 570 km s^{-1} (apocenter) (derived from Chu et al. 2018); S0-102 – orbital velocity: 4,810 km s^{-1} (pericenter), 2,100 km s^{-1} ($r = a$), 920 km s^{-1} (apocenter) (derived from Meyer et al. 2012)

Relationship to SETI: Use for gravitational assists by ETIs? (c.f., Dyson 1963) – maximum achieved ballistic speed limited by stellar radius, would work best for stellar remnants

v **(fastest, unbound):** $1{,}755 \pm 50$ km s^{-1} – S5-HVS1 [575]

Description: Highest space velocity of Milky Way-originating star unbound to Galaxy

Evaluation as true superlative: R? – Speculation about much faster (up to mildly relativistic) stars on the tail of the velocity distribution (Guillochon & Loeb 2015).

S5-HVS1 *is sidereal source*

S5-HVS1 designation in Simbad: HE 2251-5127

Reason for selection of S5-HVS1: Explicit superlative (for stars)

Works where S5-HVS1 referred to as superlative: Koposov et al. (2020)

References for data on S5-HVS1: Koposov et al. (2020)

Relationship to SETI: Use for gravitational assists by ETIs? – maximum achieved ballistic speed limited by stellar radius, would work best for stellar remnants.

P_{SMBH} **(shortest):** 7.6 ± 0.3 yr – S4711 [574]

Description: Star with the shortest orbital period around Sgr A* (shortest Galactic revolution period)

Evaluation as true superlative: ✕ – Shorter orbital periods possible even closer to supermassive black holes, and may be implicated in quasi-periodic erupting AGNs like the Anomaly GSN 069. Faint stars near Sgr A* that may venture closer are undetectable as of yet.

S4711 *is sidereal source*

Reason for selection of S4711: Explicit superlative

Works where S4711 referred to as superlative: Peißker et al. (2020)

References for data on S4711: Peißker et al. (2020)
Other works on S4711: Peissker et al. (2020); Peißker et al. (2020)
Relationships between S4711 and other Exotica Catalog objects: Within the sky region occupied by: Central Cluster [343]; Orbital primary: Sgr A* [471]; Adjacent on sky to (sharing parent object with): G2 [669], IRS 16E [604], IRS 16C [668], S0-2 [667]

Alternative superlative object(s): S0-102: former explicit superlative – period: 11.5 yr (Meyer et al. 2012)

$q_{\rm SMBH}$ **(closest):** 12.6 ± 9.3 AU – S4711 [574]

Description: Smallest pericenter in orbit around Sgr A*
Evaluation as true superlative: ✗ – Tighter possible even closer to supermassive black holes (in principle down to 3 Schwarzschild radii for circular orbits and ~ 1 Schwarzschild radius for elliptical orbits around large SMBHs). Faint stars near Sgr A* that may venture closer are undetectable as of yet.

S4711 *is sidereal source*
Reason for selection of S4711: Explicit superlative
Works where S4711 referred to as superlative: Peißker et al. (2020)
References for data on S4711: Peißker et al. (2020)
Other works on S4711: Peissker et al. (2020); Peißker et al. (2020)
Relationships between S4711 and other Exotica Catalog objects: Within the sky region occupied by: Central Cluster [343]; Orbital primary: Sgr A* [471]; Adjacent on sky to (sharing parent object with): G2 [669], IRS 16E [604], IRS 16C [668], S0-2 [667]

Alternative superlative object(s): S0-16: former explicit superlative – pericenter: 45 ± 16 AU (Ghez et al. 2005); S0-2 – pericenter: 109 AU (Chu et al. 2018)

2.5 Collapsed stars

2.5.1 White dwarfs

M (smallest): 0.16 M$_\odot$ – SDSS J222859.93+362359.6 [576]; 0.13–0.16 M$_\odot$ – NLTT 11748 [243]

Description: Lowest mass
Evaluation as true superlative: ? – Product of binary interaction, with unclear limits

SDSS J222859.93+362359.6 *is sidereal source*
Reason for selection of SDSS J222859.93+362359.6: Among lowest we found in literature; noted to be lowest mass *pulsating* white dwarf known in Hermes et al. (2013)
References for data on SDSS J222859.93+362359.6: Hermes et al. (2013)

NLTT 11748 *is sidereal source*
Reason for selection of NLTT 11748: Among lowest we found in literature
Notes on NLTT 11748: Mass: 0.16 M$_\odot$ (Kawka & Vennes 2009), 0.18 M$_\odot$ (Kilic et al. 2010b), 0.13–0.16 M$_\odot$ (Kaplan et al. 2014a)
References for data on NLTT 11748: Kaplan et al. (2014a)
Other works on NLTT 11748: Kawka et al. (2010); Steinfadt et al. (2010); Kaplan et al. (2014a); Kawka & Vennes (2009); Kilic et al. (2010a)

Alternative superlative object(s): SDSS J0917+46 – formerly the lowest mass white dwarf known, mass: 0.17 M$_\odot$ (Kilic et al. 2007a)

M (largest): 1.36–1.37 M$_\odot$ – U Sco [577]

Description: Highest mass
Evaluation as true superlative: ✓ – Near Chandrasekhar limit for maximum mass of white dwarfs

U Sco *is sidereal source*
Reason for selection of U Sco: Among highest we found in literature, with relatively small uncertainty in mass

Notes on U Sco: Mass: 1.37 $M_\odot$ (Hachisu & Kato 2001), 1.36 $M_\odot$ (Shara et al. 2018)
References for data on U Sco: Hachisu & Kato (2001); Shara et al. (2018)

Alternative superlative object(s): T CrB – mass: 1.37 $M_\odot$ (Hachisu & Kato 2001), 1.32 $M_\odot$ (Shara et al. 2018); V745 Sco – mass: 1.35 $M_\odot$ (Hachisu & Kato 2001), 1.40 $M_\odot$ (Shara et al. 2018); RS Oph – mass: 1.35–1.377 $M_\odot$ (Hachisu & Kato 2001), 1.31 $M_\odot$ (Shara et al. 2018); U Sco – mass: 1.37 $M_\odot$ (Hachisu & Kato 2001), 1.36 $M_\odot$ (Shara et al. 2018)

M (largest, non-interacting): 1.310–1.335 $M_\odot$ – LHS 4033 [578]

Description: Highest mass white dwarf not currently in an interacting binary system
Evaluation as true superlative: ✓ – Fairly near Chandrasekhar limit for maximum mass of white dwarfs

LHS 4033 *is sidereal source*
Reason for selection of LHS 4033: Explicit superlative
Works where LHS 4033 referred to as superlative: Dahn et al. (2004)
References for data on LHS 4033: Dahn et al. (2004)

Alternative superlative object(s): RE J0317-853 – mass: 1.28–1.46 $M_\odot$, explicitly noted possibility of being most massive (Külebi et al. 2010)

$T_{\rm eff}$ (coldest): < 3,000 K – PSR J2222-0137 B [579]

Description: Lowest effective temperature
Evaluation as true superlative: ✕ ? – Cannot be evaluated without a measurement of temperature. For these ultracool white dwarfs, more massive white dwarfs cool fastest, but this temperature regime does not seem to be commonly modeled. The Bédard et al. (2020) white dwarf models, as posted on http://www.astro.umontreal.ca/~bergeron/CoolingModels/ imply that 0.6 $M_\odot$ white dwarfs can cool to 1,500–2,300 K in 13.5 Gyr, with the fastest cooling, highest mass 1.3 $M_\odot$ models dropping below 1,500 K in 4–6 Gyr.

PSR J2222-0137 B *is sidereal source*
PSR J2222-0137 B designation in Simbad: PSR J2222-0137
Reason for selection of PSR J2222-0137 B: Explicit superlative
Notes on PSR J2222-0137 B: White dwarf is not directly detected, but inferred from pulsar timing; age: ∼ 4 Gyr (Cognard et al. 2017)
Works where PSR J2222-0137 B referred to as superlative: Kaplan et al. (2014b)
References for data on PSR J2222-0137 B: Kaplan et al. (2014b)
Other works on PSR J2222-0137 B: Cognard et al. (2017); Deller et al. (2013)

Alternative superlative object(s): WD 0346+246 – temperature: 3,750 K (Oppenheimer et al. 2001), 3,780 K (Bergeron 2001), 3,650 K (Kilic et al. 2012), among lowest of directly detected WDs

$T_{\rm eff}$ (hottest): 250,000 K – RX J0439.8-6809 [580]

Description: Highest (mean) effective temperature
Evaluation as true superlative: ✓ – Expected maximum from predicted stellar evolutionary tracks

RX J0439.8-6809 *is sidereal source*
Reason for selection of RX J0439.8-6809: Explicit superlative
Works where RX J0439.8-6809 referred to as superlative: Werner & Rauch (2015)
References for data on RX J0439.8-6809: Werner & Rauch (2015)

Alternative superlative object(s): H1504+64 – temperature: 200,000 K, explicitly second hottest known in Werner & Rauch (2015)

B **(strongest):** 0.5–1 GG – PG 1031+234 [581]

Description: Strongest (polar) magnetic field
Status as true superlative unknown

PG 1031+234 *is sidereal source*
Reason for selection of PG 1031+234: Explicit superlative; highest in Wickramasinghe & Ferrario (2000)

Works where PG 1031+234 referred to as superlative: Schmidt et al. (1986); Latter et al. (1987)
References for data on PG 1031+234: Wickramasinghe & Ferrario (2000)

t **(oldest):** 11.5 Gyr – WD 0346+246 [582]

Description: White dwarf with greatest age as observed
Evaluation as true superlative: ✓ – Approaches age of Universe. White dwarfs may have formed when the Universe was significantly younger, although note there is a delay time before intermediate mass stars form the first white dwarfs. Additionally, it is generally thought that Population III stars were high mass, although under some conditions low mass Population III stars may have formed (Greif et al. 2011; Stacy & Bromm 2014). According to Ishiyama et al. (2016), surviving low mass Population III stars in the halo would be concentrated towards the Galactic Center or in dwarf galaxies; presumably white dwarf remnants would follow the same pattern and would be too faint to be detectable at present.

WD 0346+246 *is sidereal source*
WD 0346+246 designation in Simbad: [HSH97] WD 0346+246
Reason for selection of WD 0346+246: Explicit superlative
Works where WD 0346+246 referred to as superlative: Kilic et al. (2012)
References for data on WD 0346+246: Kilic et al. (2012)

v **(fastest, inflated remnant):** $\sim 2{,}400\ \mathrm{km\,s^{-1}}$ – D6-3 [250]

Description: Highest Galactocentric velocity for white dwarf, including those puffed out by energy deposition
Evaluation as true superlative: ?/R? – If we are restricting ourselves to hyperrunaway stars like D6-3, then this may be indeed be a Superlative. If we include all white dwarfs or white dwarf-like objects, then much faster stars – and their white dwarf remnants – presumably exist although only on the far tail of the velocity distribution (Guillochon & Loeb 2015).

D6-3 *is sidereal source*
D6-3 designation in Simbad: Gaia DR2 2156908318076164224
D6-3 also known as: Gaia DR2 2156908318076164224; LSPM J1852+6202
Reason for selection of D6-3: Explicitly noted to be probable superlatives among stars and white dwarfs
Caveats about selection of D6-3: Radius of D6-3 implies it is comparable to hot subdwarf in size, not white dwarf; Shen et al. (2018) argues that it is/was a white dwarf that was inflated when its companion underwent a Type Ia supernova
Notes on D6-3: Galactocentric velocity: 1,400–9,000 $\mathrm{km\,s^{-1}}$ (99.7% credible interval)
Works where D6-3 referred to as superlative: Shen et al. (2018)
References for data on D6-3: Shen et al. (2018)
Other works on D6-3: Shen et al. (2018)

v_{trans} **(fastest):** $\sim 350\ \mathrm{km\,s^{-1}}$ – LP 400-22 [583]

Description: Highest transverse (non-radial) velocity as observed from Earth for white dwarf
Evaluation as true superlative: ✕ – Presumably hypervelocity white dwarfs exist, and hyperrunaway objects like D6-3 should settle back down into more typical white dwarfs. Because of their low space density and great distances, they cannot as of yet be detected.

LP 400-22 *is sidereal source*
Reason for selection of LP 400-22: Explicit superlative
Notes on LP 400-22: Calculated from *Gaia* distance and proper motion; Kilic et al. (2013) proposes the system is further than proposed by Kawka et al. (2006) and thus has speed $> 800\ \mathrm{km\,s^{-1}}$, but *Gaia* data favors a closer distance; actually a white dwarf-white dwarf binary
Works where LP 400-22 referred to as superlative: Kawka et al. (2006)
References for data on LP 400-22: Gaia Collaboration et al. (2018b)

2.5.2 Neutron stars

M (smallest): $1.02 \pm 0.17\ \mathrm{M_\odot}$ – 4U 1538-522 [584]

Description: Lowest mass
Status as true superlative unknown

4U 1538-522 *is sidereal source*
Reason for selection of 4U 1538-522: Consistently small estimated mass, among lowest we found in literature
Notes on 4U 1538-522: Neutron star mass: ~ 0.87–1.0 $M_\odot$ (Rawls et al. 2011), 1.02 ± 0.17 $M_\odot$ (Falanga et al. 2015)
References for data on 4U 1538-522: Falanga et al. (2015)

Alternative superlative object(s): PSR J1840-4631 – mass: ~ 0.1 $M_\odot$ suggested by (Chen 2016); 4U 1746-37 – mass: $0.41^{+0.70}_{-0.30}$ $M_\odot$ according to (Li et al. 2015); PSR J1518+4904: – mass: $0.72^{+0.51}_{-0.58}$ $M_\odot$, noted as possible superlative (Janssen et al. 2008); PSR J0453+1559 – companion mass: 1.174 ± 0.004 $M_\odot$, unclear if actually NS, would be possible superlative (Martinez et al. 2015)

M (largest): $2.14^{+0.10}_{-0.09}$ $M_\odot$ – MSP J0740+6620 [585]; 2.40 ± 0.12 $M_\odot$ – PSR B1957+20 [319]

Description: Highest mass
Evaluation as true superlative: ? / ✓ – MSP J0740+6620 has a reliable mass but larger masses may be possible, depending on neutron star equation of state. PSR B1957+20, if the mass is reliable, is beyond some recent estimates of the maximum mass (e.g., Margalit & Metzger 2017a); a very conservative limit on the mass is ~ 2.5 $M_\odot$ (Abbott et al. 2020).

MSP J0740+6620 *is sidereal source*
MSP J0740+6620 designation in Simbad: PSR J0740+6620
Reason for selection of MSP J0740+6620: Explicit superlative
Works where MSP J0740+6620 referred to as superlative: Cromartie et al. (2020)
References for data on MSP J0740+6620: Cromartie et al. (2020)

PSR B1957+20 *is sidereal source*
PSR B1957+20 also known as: The Black Widow pulsar
Reason for selection of PSR B1957+20: Among highest we found in literature with relatively small error bars
Caveats about selection of PSR B1957+20: Constraints on tidal deformability of neutron stars from GW170817 support a maximum mass of only 2.1–2.3 $M_\odot$ (Margalit & Metzger 2017a; Rezzolla et al. 2018; Shibata et al. 2019; Raaijmakers et al. 2020)
Notes on PSR B1957+20: Mass: conservatively > 1.66 $M_\odot$ (van Kerkwijk et al. 2011); high masses seem to be characteristic of black widow pulsars, presumably because of mass transfer, but the measurements still face systematic issues (Özel & Freire 2016; Lattimer 2019)
References for data on PSR B1957+20: van Kerkwijk et al. (2011)
Other works on PSR B1957+20: Huang et al. (2012); Fruchter et al. (1988); Kluzniak et al. (1988)
Relationships between PSR B1957+20 and other Exotica Catalog objects: Within the sky region occupied by: PSR B1957+20 bow shock [378]

Alternative superlative object(s): 4U 1700-37 (HD 153919) – accreting component mass: 2.44 ± 0.27 $M_\odot$ but unclear if NS (Clark et al. 2002), 1.96 ± 0.19 $M_\odot$ (Falanga et al. 2015), NS mass recipient favored (Martinez-Chicharro et al. 2018); PSR J2215+5135 – mass: $2.27^{+0.17}_{-0.33}$ $M_\odot$ (Linares et al. 2018); GW 190814 progenitor secondary – mass: $2.58^{+0.08}_{-0.09}$ $M_\odot$ – object now consumed by black hole, nature as NS unclear and not favored by Abbott et al. (2020), position not localized enough

$L_{\rm rot}$ (brightest): 130,000 $L_\odot$ – PSR J0537-6910 [586]

Description: Neutron star with greatest spin-down luminosity
Evaluation as true superlative: ? – Possibility of rapidly spinning magnetars in young supernova remnants with much higher spindown luminosities, perhaps as progenitors of observed magnetars. Because the spindown period of these objects would be so short, they would be rare and hard to catch. Magnetars with millisecond rotation periods (Duncan & Thompson 1992) are hypothesized to be central engines in gamma-ray bursts (Usov 1992) and superluminous supernovae (Kasen & Bildsten 2010), although these would spin down within minutes (Metzger et al. 2011). Metzger et al. (2017) further proposes the years-old magnetars could power fast radio bursts like FRB 121102.

PSR J0537-6910 *is sidereal source*
Reason for selection of PSR J0537-6910: Explicit superlative
Works where PSR J0537-6910 referred to as superlative: Marshall et al. (1998); Ferdman et al. (2018)

References for data on PSR J0537-6910: Marshall et al. (1998); Ferdman et al. (2018)
Other works on PSR J0537-6910: Andersson et al. (2018)
Works on PSR J0537-6910's host: Pietrzyński et al. (2019)
Relationships between PSR J0537-6910 and other Exotica Catalog objects: Adjacent on sky to (sharing parent object with): 30 Dor [619], CAL 83 nebula [382], Melnick 34 [600], N159F [385], NS 1987A [592], OGLE LMC-CEP-4506 [702], R136 a1 [566], SN 1987A [375]
Relationships between PSR J0537-6910 and objects in I17: Within the sky region occupied by: LMC

L_{rot} (dimmest): 6.8×10^{-6} $L_{\odot}$ – PSR J2144-3933 [587]

Description: Neutron star with smallest spin-down luminosity
Evaluation as true superlative: ✗ – Ancient ($\sim$ 10 Gyr) unrecycled neutron stars presumably spin even slower and are expected to be very numerous, but they are essentially impossible to detect with current techniques.

PSR J2144-3933 *is sidereal source*
Reason for selection of PSR J2144-3933: Explicit superlative
Notes on PSR J2144-3933: Also among closest known; spin period: 8.51 s; characteristic age: 333 Myr; thermal luminosity: $\lesssim 5 \times 10^{-7}$ $L_{\odot}$
Works where PSR J2144-3933 referred to as superlative: Tiengo et al. (2011)
References for data on PSR J2144-3933: Tiengo et al. (2011)
Other works on PSR J2144-3933: Guillot et al. (2019); Verbiest et al. (2012)

T_{eff} (coldest): $<$ 42,000 K – PSR J2144-3933 [587]

Description: Lowest effective temperature
Evaluation as true superlative: ✗ – Ancient ($\sim$ 10 Gyr) unrecycled neutron stars could achieve very low temperatures ($\lesssim$ 100 K in absence of ISM accretion, due to low heat capacity; Yakovlev & Pethick 2004) and are expected to be very numerous, but they are essentially impossible to detect with current techniques. ISM accretion may set a temperature floor in the Solar neighborhood, but many old NSs could be ejected into galactic halos or even entirely into intergalactic space.

PSR J2144-3933 *is sidereal source*
Reason for selection of PSR J2144-3933: Explicit superlative
Notes on PSR J2144-3933: Also among closest known; spin period: 8.51 s; characteristic age: 333 Myr; thermal luminosity: $\lesssim 5 \times 10^{-7}$ $L_{\odot}$
Works where PSR J2144-3933 referred to as superlative: Guillot et al. (2019)
References for data on PSR J2144-3933: Guillot et al. (2019)
Other works on PSR J2144-3933: Verbiest et al. (2012); Tiengo et al. (2011)

P_{rot} (fastest): 0.89 ms – XTE J1739-285 [588]

Description: Shortest rotation period
Evaluation as true superlative: ✓ – Near rotational breakup limit for NSs

XTE J1739-285 *is sidereal source*
Reason for selection of XTE J1739-285: Explicit superlative
Caveats about selection of XTE J1739-285: Not confirmed yet according to Patruno et al. (2018)
Notes on XTE J1739-285: Inferred from X-ray oscillations
Works where XTE J1739-285 referred to as superlative: Kaaret et al. (2007)
References for data on XTE J1739-285: Kaaret et al. (2007)

P_{rot} (slowest): $36{,}200 \pm 110$ s – AX J1910.7+0917 [589]

Description: Longest rotation period
Evaluation as true superlative: ? – Product of binary interaction, with unclear limits

AX J1910.7+0917 *is sidereal source*
Reason for selection of AX J1910.7+0917: Explicit superlative
Notes on AX J1910.7+0917: Inferred from X-ray periodicity

Works where AX J1910.7+0917 referred to as superlative: Sidoli et al. (2017)
References for data on AX J1910.7+0917: Sidoli et al. (2017)
Other works on AX J1910.7+0917: Rodes-Roca et al. (2013)

B **(weakest):** 0.085–2 GG – IGR J00291+5934 [590]

Description: Strongest dipolar magnetic field
Status as true superlative unknown

IGR J00291+5934 *is sidereal source*
Reason for selection of IGR J00291+5934: Lowest of accreting millisecond pulsars in Mukherjee et al. (2015); smallest value we found in literature
Notes on IGR J00291+5934: Range in B from different methods
References for data on IGR J00291+5934: Patruno (2010); Mukherjee et al. (2015)

B **(strongest):** 2 PG – SGR 1806-20 [267]; 0.70 PG – SGR 1900+14 [591]

Description: Strongest dipolar magnetic field
Status as true superlative unknown

SGR 1806-20 *is sidereal source*
Reason for selection of SGR 1806-20: Explicit superlative; largest value listed in Olausen & Kaspi (2014) magnetar catalog
Notes on SGR 1806-20: Kouveliotou et al. (1998) gives magnetic field strengths of 0.2 and 0.8 PG, depending on spindown theory used
Works where SGR 1806-20 referred to as superlative: Kouveliotou et al. (1998); Tendulkar et al. (2016)
References for data on SGR 1806-20: Olausen & Kaspi (2014)
Other works on SGR 1806-20: Hurley et al. (2005); Palmer et al. (2005); Terasawa et al. (2005)

SGR 1900+14 *is sidereal source*
Reason for selection of SGR 1900+14: Second largest value listed in Olausen & Kaspi (2014) magnetar catalog
Notes on SGR 1900+14: Kouveliotou et al. (1999) gives magnetic field strengths of 0.2 and 0.8 PG, depending on spindown theory used
References for data on SGR 1900+14: Olausen & Kaspi (2014)

Alternative superlative object(s): 1E 1841-045 – magnetic field strength: 0.69 PG (Olausen & Kaspi 2014)

t **(youngest):** 33 yr (2020) – NS 1987A [592]

Description: Neutron star with smallest age as observed
Evaluation as true superlative: R/L – Most recent known core collapse supernova in Local Group; dynamic category based on transient events. Note several supernovae happen per second are expected in our Hubble volume.

NS 1987A *is sidereal source*
NS 1987A designation in Simbad: SN 1987A
Reason for selection of NS 1987A: Explicit superlative; most recent nearby supernova where non-ultraluminous neutron star detection likely
Caveats about selection of NS 1987A: Claimed detection of gas "blob" heated by NS of SN 1987A in Cigan et al. (2019), but not prominently discussed; Page et al. (2020) favors interpretation of heating by thermal emission from NS; may need confirmation
Works where NS 1987A referred to as superlative: Page et al. (2020)
References for data on NS 1987A: Page et al. (2020)
Works on NS 1987A's host: Pietrzyński et al. (2019)
Relationships between NS 1987A and other Exotica Catalog objects: Within the sky region occupied by: SN 1987A [375]; Adjacent on sky to (sharing parent object with): 30 Dor [619], CAL 83 nebula [382], Melnick 34 [600], N159F [385], OGLE LMC-CEP-4506 [702], PSR J0537-6910 [586], R136 a1 [566]
Relationships between NS 1987A and objects in I17: Within the sky region occupied by: LMC

v_{trans} **(fastest):** $1{,}083^{+103}_{-90}\ \mathrm{km\,s^{-1}}$ – PSR B1508+55 [593]

Description: Neutron star with largest transverse velocity as viewed from Earth

Evaluation as true superlative: ? – Speculation about much faster (up to mildly relativistic) hypervelocity stars, which would evolve into mildly relativistic stellar remnants

PSR B1508+55 *is sidereal source*
Reason for selection of PSR B1508+55: Explicit superlative
Works where PSR B1508+55 referred to as superlative: Chatterjee et al. (2005)
References for data on PSR B1508+55: Chatterjee et al. (2005)

Alternative superlative object(s): IGR J11014-6103: Tomsick et al. (2012) associates it with the supernova remnant MSH 11-61A and argues its v_{trans} is 2,400–2,900 $\mathrm{km\,s^{-1}}$ – Halpern et al. (2014) argues for a smaller distance and $v_{\mathrm{trans}} \approx 800\ \mathrm{km\,s^{-1}}$.

2.5.3 Radio pulsars

$\mathbf{P}_{\mathrm{rot}}$ (fastest): 1.397 ms – PSR J1748-2446ad [594]

Description: Shortest rotation period
Evaluation as true superlative: ✓ – Near rotational breakup limit for NSs

PSR J1748-2446ad *is sidereal source*
Reason for selection of PSR J1748-2446ad: Explicit superlative
Works where PSR J1748-2446ad referred to as superlative: Hessels et al. (2006); Bassa et al. (2017a)
References for data on PSR J1748-2446ad: Hessels et al. (2006); Bassa et al. (2017a)

Alternative superlative object(s): PSR J0952-0607 – spin period: 1.414 ms, second-fastest known, fastest outside of globular cluster (Bassa et al. 2017a)

$\mathbf{P}_{\mathrm{rot}}$ (fastest, unrecycled): 16.11 ms – PSR J0537-6910 [586]

Description: Shortest rotation period of pulsar that has not been spun up by mass transfer from binary companion
Status as true superlative unknown

PSR J0537-6910 *is sidereal source*
Reason for selection of PSR J0537-6910: Explicit superlative; too young to be recycled
Works where PSR J0537-6910 referred to as superlative: Andersson et al. (2018)
References for data on PSR J0537-6910: Andersson et al. (2018)
Other works on PSR J0537-6910: Marshall et al. (1998); Ferdman et al. (2018)
Relationships between PSR J0537-6910 and other Exotica Catalog objects: Adjacent on sky to (sharing parent object with): 30 Dor [619], CAL 83 nebula [382], Melnick 34 [600], N159F [385], NS 1987A [592], OGLE LMC-CEP-4506 [702], R136 a1 [566], SN 1987A [375]
Relationships between PSR J0537-6910 and objects in I17: Within the sky region occupied by: LMC

$\mathbf{P}_{\mathrm{rot}}$ (slowest): 23.5 s – PSR J0250+5854 [595]

Description: Longest rotation period
Evaluation as true superlative: ? – Ancient neutron stars may have longer rotation periods, but they may not radiate coherent radio emission. Previously, radio emission has been assumed to be suppressed by the conventional pulsar "death line", although PSR 2144-3933 is a radio pulsar well beyond it (Tan et al. 2018).

PSR J0250+5854 *is sidereal source*
Reason for selection of PSR J0250+5854: Explicit superlative
Notes on PSR J0250+5854: Spindown luminosity: $2.1 \times 10^{-5}\ \mathrm{L_{\odot}}$; characteristic age: 13.7 Myr
Works where PSR J0250+5854 referred to as superlative: Tan et al. (2018)
References for data on PSR J0250+5854: Tan et al. (2018)

2.5.4 Black holes

M (smallest): $3.3^{+2.8}_{-0.7}\ \mathrm{M_{\odot}}$ – 2MASS J05215658+4359220 [596]

Description: Smallest mass
Evaluation as true superlative: ✓? – Degeneracy pressure should prevent total collapse of stable white dwarfs and neutron

stars, which would generally set a lower mass limit of $\sim 2.2\ M_\odot$, although the exact boundary is unclear. Broadly speaking, 2MASS J05215658+4359220 (if authentic) is near this limit, although GW 190814 is evidence for objects much closer to the limit.

2MASS J05215658+4359220 *is sidereal source*
Reason for selection of 2MASS J05215658+4359220: Implicit superlative: stated to be more massive than known NSs, less massive than known BHs
Caveats about selection of 2MASS J05215658+4359220: Could be very massive neutron star; nature disputed by van den Heuvel & Tauris (2020) based on uncertainty in companion cool giant star, defended by Thompson et al. (2020)
References for data on 2MASS J05215658+4359220: Thompson et al. (2019)

Alternative superlative object(s): GW 190814 progenitor secondary – mass: $2.58^{+0.08}_{-0.09}\ M_\odot$ – object now subsumed by black hole, nature as BH unclear although favored by Abbott et al. (2020), position not localized enough

2.6 Interacting binary stars

P (shortest): 321.25 ± 0.25 s – HM Cnc [597]

Description: Shortest orbital period
Evaluation as true superlative: R – Much smaller orbital periods (down to ~ 10 s) possible for double degenerate binaries involving a white dwarf, and may be responsible for Type Ia supernovae. These would be very short-lived from gravitational wave emission, and thus rare.

HM Cnc *is sidereal source*
Reason for selection of HM Cnc: Explicit superlative
Works where HM Cnc referred to as superlative: Israel et al. (2002); Roelofs et al. (2010)
References for data on HM Cnc: Israel et al. (2002)

EIRP (brightest): $\sim (0.7\text{–}6) \times 10^7\ L_\odot$ – NGC 5907 ULX [598]

Description: Interacting binary with highest apparent isotropic luminosity
Status as true superlative unknown

NGC 5907 ULX *is sidereal source*
NGC 5907 ULX designation in Simbad: NGC 5907 ULX-1
Reason for selection of NGC 5907 ULX: Explict superlative of pulsating ULXs, which certainly are accreting binaries
Notes on NGC 5907 ULX: Luminosity fluctuates; the emission could be beamed and thus the actual luminosity may be much lower, however Belfiore et al. (2020) interpret its nebula as resulting from sustained power of $\sim 3 \times 10^7\ L_\odot$
Works where NGC 5907 ULX referred to as superlative: Song et al. (2020)
References for data on NGC 5907 ULX: Israel et al. (2017)
Works on NGC 5907 ULX's host: Tully et al. (2013)

2.7 Stellar groups

2.7.1 Detached binaries

M (smallest): $7.4^{+2.4}_{-1.8}$–$18.2^{+4.7}_{-3.8}\ M_J$ – TWA 42 [599]

Description: Binary stellar system with smallest total mass
Status as true superlative unknown

TWA 42 *is sidereal source*
Reason for selection of TWA 42: Explicit superlative
Notes on TWA 42: Mass determination depends on association of system with TW Hydrae Association, but would be $\sim 18\ M_J$ in field
Works where TWA 42 referred to as superlative: Best et al. (2017)
References for data on TWA 42: Best et al. (2017)

Alternative superlative object(s): DENIS-P J035726.9-441730 – 14–15 M_J (Gagné et al. 2014)

M (largest): 266^{+38}_{-35} $M_\odot$ – Melnick 34 [600]

Description: Binary stellar system with largest total mass
Evaluation as true superlative: ✓ – Both components extremely massive (> 100 $M_\odot$) and starting to approach expected upper mass limit for stars; more massive components would be rare

Melnick 34 *is sidereal source*
Melnick 34 designation in Simbad: Cl* NGC 2070 MEL 34
Reason for selection of Melnick 34: Explicit superlative
Notes on Melnick 34: Possibly a colliding wind binary
Works where Melnick 34 referred to as superlative: Tehrani et al. (2019)
References for data on Melnick 34: Tehrani et al. (2019)
Relationships between Melnick 34 and other Exotica Catalog objects: Within the sky region occupied by: 30 Dor [619]; Adjacent on sky to (sharing parent object with): CAL 83 nebula [382], N159F [385], NS 1987A [592], OGLE LMC-CEP-4506 [702], PSR J0537-6910 [586], R136 a1 [566], SN 1987A [375]
Relationships between Melnick 34 and objects in I17: Within the sky region occupied by: LMC

$M_2 \sin i$ (smallest): 0.76 M_J – PSR J2322-2650 [601]

Description: Smallest stellar object in a binary system
Evaluation as true superlative: R? – Result of binary interaction. In some systems, this leads to the complete disruption of the secondary, so smaller objects near disruption are likely to exist for short periods of time. Mass limits on long-lived secondaries are unclear, however.

PSR J2322-2650 *is sidereal source*
Reason for selection of PSR J2322-2650: Implicit superlative: smallest non-planetary value listed in Spiewak et al. (2018)
Notes on PSR J2322-2650: Planets can be much smaller, but they are believed to have formed differently than stars through core accretion; the secondary in PSR J2322-2650 is an eroded star
References for data on PSR J2322-2650: Spiewak et al. (2018)

P (shortest): 414.79 s – ZTF J153932.16+502738.8 [602]

Description: Shortest orbital period
Evaluation as true superlative: R – Much smaller orbital periods (down to ∼ 10 s) possible for double degenerate binaries involving a white dwarf, and may be responsible for Type Ia supernovae. These would be very short-lived from gravitational wave emission, and thus rare. White dwarfs very near merger would begin mass transfer, and thus be (briefly) interacting before merger or destruction.

ZTF J153932.16+502738.8 *is sidereal source*
Reason for selection of ZTF J153932.16+502738.8: Implicit superlative: only two binaries with shorter periods according to Burdge et al. (2019), both interacting binaries
Notes on ZTF J153932.16+502738.8: Separation: 78,000 km; barycentric orbital velocities: 300 $km\,s^{-1}$, 880 $km\,s^{-1}$; component masses: 0.61 $M_\odot$, 0.21 $M_\odot$
References for data on ZTF J153932.16+502738.8: Burdge et al. (2019)

Relationship to SETI: Close double-degenerate binaries can be used to build Dyson gravity engine, high orbital speed can be used to launch craft at speeds comparable to components (Dyson 1963)

2.7.2 Detached multiples

$N_\star$ (most): 7 – 65 UMa [603]

Description: Most number of component stars
Evaluation as true superlative: R? – Empirically very rare, but no specific reason to expect there to be a limit. No observational biases we are aware of would prevent detection of more superlative systems if they were common.

65 UMa *is sidereal source*
65 UMa also known as: HD 103483+HD 103498; HR 4560+HR 4561; HIP 58112+58117

Reason for selection of 65 UMa: Largest number of components we found in literature; most confident septuple in Tokovinin (2018)
Caveats about selection of 65 UMa: Tokovinin (2018) remarks that no septuple case is completely certain: (Da,Db) may be part of moving group instead, and its binary nature is not yet confirmed
Notes on 65 UMa: Hierarchy: (Da,Db)(C(B(Ab(Aa1,Aa2)))); D–A separation: 63.2″
References for data on 65 UMa: Tokovinin (2018)
Other works on 65 UMa: Tokovinin (2018)

Alternative superlative object(s): ν Sco – septuple in Tokovinin (2018); AR Cas – septuple in Tokovinin (2018); Castor – nearby certain sextuple system

$N_\star$ (most): 5 – 65 UMa [603]

Description: Greatest number of levels in hierarchical grouping (ex., a binary has one level, a wider pair of binaries has two levels, a much wider pair of those quadruple systems has three, etc.)
Evaluation as true superlative: R? – Empirically very rare, but no specific reason to expect there to be a limit. No observational biases we are aware of would prevent detection of more superlative systems if they were common.

65 UMa *is sidereal source*
Reason for selection of 65 UMa: Largest number (5) we found in literature; Zasche et al. (2012) and Tokovinin (2018) remark on its uniqueness
Caveats about selection of 65 UMa: Tokovinin (2018) remarks that no septuple case is completely certain: (Da,Db) may be part of moving group instead, and its binary nature is not yet confirmed
Notes on 65 UMa: Hierarchy: (Da,Db)(C(B(Ab(Aa1,Aa2)))); D–A separation: 63.2″
References for data on 65 UMa: Tokovinin (2018)
Other works on 65 UMa: Tokovinin (2018)

2.7.3 Non-hierarchical stellar groups

ρ (highest): $\gtrsim 10^8$ M$_\odot$ pc^{-3} – IRS 13E [604]

Description: Group of stars that are not binaries nor organized in a hierarchical fashion like multiple systems with the highest density
Status as true superlative unknown

IRS 13E *is sidereal source*
IRS 13E designation in Simbad: GCIRS 13E
Reason for selection of IRS 13E: Explicit superlative
Caveats about selection of IRS 13E: Not known if actual bound group; may be chance projection effect
Works where IRS 13E referred to as superlative: Paumard et al. (2006); Fritz et al. (2010)
References for data on IRS 13E: Paumard et al. (2006)
Other works on IRS 13E: Zhu et al. (2020); Wang et al. (2020); Paumard et al. (2006); Fritz et al. (2010)
Works on IRS 13E's host: Gravity Collaboration et al. (2019b)
Relationships between IRS 16E and other Exotica Catalog objects: Within the sky region occupied by: Central Cluster [343]; Orbital primary: Sgr A* [471]; Adjacent on sky to (sharing parent object with): G2 [669], IRS 16C [668], S0-2 [667], S4711 [574]

Alternative superlative object(s): Central Cluster core: higher density according to Paumard et al. (2006)

2.7.4 Star clusters

M (largest): $(8 \pm 2) \times 10^7$ M$_\odot$ – NGC 7252 W3 [605]

Description: Largest (stellar) mass
Evaluation as true superlative: R – Even more massive clusters constrained by observational searches, and possibly ISM physics. Larger star clusters should be easier to detect. Still larger clusters may have been prevalent at high redshift, allowed by different ISM conditions.

NGC 7252 W3 *is sidereal source*

NGC 7252 W3 designation in Simbad: [WSL93] 3
Reason for selection of NGC 7252 W3: Explicit superlative
Caveats about selection of NGC 7252 W3: Noted to resemble ultracompact dwarf galaxies in Maraston et al. (2004)
Notes on NGC 7252 W3: According to Maraston et al. (2004), likely to be a genuine star cluster and not a galaxy
Works where NGC 7252 W3 referred to as superlative: Maraston et al. (2004); Bastian et al. (2013)
References for data on NGC 7252 W3: Bastian et al. (2013)

2.7.5 Open star clusters

$\rho_{1/2}$ **(highest, Milky Way):** $\sim 6{,}000\ \mathrm{M}_\odot\ \mathrm{pc}^{-3}$ – HD 97950 [606]

Description: Open star cluster with the greatest density within half-mass radius
Evaluation as true superlative: M – Constrained by observations of high mass Milky Way star clusters

HD 97950 *is sidereal source*
Reason for selection of HD 97950: Explicit superlative; highest value we found in literature
Notes on HD 97950: Core of NGC 3603 cluster; density calculated according to total mass of 16,000 $\mathrm{M}_\odot$ and half-mass radius of 0.7 pc (Harayama et al. 2008); central density $\sim 60{,}000\ \mathrm{M}_\odot\ \mathrm{pc}^{-3}$ (Harayama et al. 2008)
Works where HD 97950 referred to as superlative: Drissen et al. (1995)
References for data on HD 97950: Harayama et al. (2008)
Other works on HD 97950: Fukui et al. (2014)
Relationships between HD 97950 and other Exotica Catalog objects: Within the sky region occupied by: NGC 3603 [359]; Adjacent on sky to (sharing parent object with): [SBD2011] 5 [686]

t **(oldest):** 9–10 Gyr – Be 17 [607]

Description: Oldest bound open cluster
Evaluation as true superlative: ✓ – Approaches age of Universe

Be 17 *is sidereal source*
Be 17 designation in Simbad: Cl Berkeley 17
Be 17 also known as: Berkeley 17
Reason for selection of Be 17: Explicit superlative
Notes on Be 17: Age: 12.6 Gyr (Friel 1995), 12^{+1}_{-2} Gyr, 10.07 Gyr (Salaris et al. 2004), 8.5–9 Gyr (Bragaglia et al. 2006)
Works where Be 17 referred to as superlative: Friel (1995); Phelps (1997); Bhattacharya et al. (2017)
References for data on Be 17: Salaris et al. (2004); Bragaglia et al. (2006)

Alternative superlative object(s): NGC 6791 – age: 8 Gyr (García-Berro et al. 2010), historically thought to be nearly as old as Be 17 (Salaris et al. 2004; Krusberg & Chaboyer 2006)

[Fe/H] (richest): 0.313 ± 0.005 – NGC 6791 [608]

Description: Highest mean iron abundance (and possibly metallicity)
Evaluation as true superlative: M – Constrained by observations of Milky Way star clusters

NGC 6791 *is sidereal source*
Reason for selection of NGC 6791: Explicit possible superlative; among highest values we found in literature
Notes on NGC 6791: [Fe/H]: 0.47 ± 0.04 (Gratton et al. 2006), 0.3 (Boesgaard et al. 2015), 0.313 ± 0.005 (Villanova et al. 2018)
Works where NGC 6791 referred to as superlative: Villanova et al. (2018)
References for data on NGC 6791: Villanova et al. (2018)

Alternative superlative object(s): NGC 6253 – metallicity equal to NGC 6791, [Fe/H]: 0.46 (Carretta et al. 2007) (compared with Gratton et al. (2006) value)

2.7.6 Globular clusters

M (largest, old): $8 \times 10^6\ \mathrm{M}_\odot$ – G1 [609]; $\leq 3\ \times 10^7\ \mathrm{M}_\odot$ – (GC) 037-B327 [610]

Description: Highest mass globular cluster that is old ($\gg 1$ Gyr; i.e., excluding super star clusters)

Evaluation as true superlative: R/L – Even more massive clusters should be brighter and easier to detect but are not found in the Milky Way. Norris & Kannappan (2011) proposes that some ultracompact dwarf galaxies are actually "giant globular clusters" with stellar masses up to 7×10^7 $M_\odot$.

G1 *is sidereal source*
G1 designation in Simbad: Mayall II
G1 also known as: Mayall II
Reason for selection of G1: Explicit superlative in Local Group
Caveats about selection of G1: Possibly stripped nucleus from dwarf galaxy
Works where G1 referred to as superlative: Meylan et al. (2001)
References for data on G1: Baumgardt et al. (2003)
Works on G1's host: McConnachie et al. (2005)
Relationships between G1 and other Exotica Catalog objects: Adjacent on sky to (sharing parent object with): (GC) 037-B327 [610], M31-EC4 [341], M32 [396], NGC 205 [398]
Relationships between G1 and objects in I17: Gravitationally bound to: M31

(GC) 037-B327 *is sidereal source*
(GC) 037-B327 designation in Simbad: Bol 37
(GC) 037-B327 also known as: Bol 37
Reason for selection of (GC) 037-B327: Explicit superlative in Local Group
Caveats about selection of (GC) 037-B327: Possibly stripped nucleus from dwarf galaxy (Ma et al. 2006b)
Notes on (GC) 037-B327: Mass: $\sim 8.5 \times 10^6$ $M_\odot$ (Barmby et al. 2002), $\sim 3 \times 10^7$ $M_\odot$ (Ma et al. 2006a), smaller than G1 and comparable to ω Cen (Cohen 2006)
Works where (GC) 037-B327 referred to as superlative: Barmby et al. (2002); Ma et al. (2006a)
References for data on (GC) 037-B327: Ma et al. (2006a); Cohen (2006)
Works on (GC) 037-B327's host: McConnachie et al. (2005)
Relationships between (GC) 037-B327 and other Exotica Catalog objects: Adjacent on sky to (sharing parent object with): M31-EC4 [341], M32 [396], G1 [609], NGC 205 [398]
Relationships between (GC) 037-B327 and objects in I17: Gravitationally bound to: M31

Alternative superlative object(s): Some ultracompact dwarf galaxies with masses up to $\sim 7 \times 10^7$ $M_\odot$ are probably globular clusters (Norris & Kannappan 2011); M85-HCC1 – mass: $(1.2 \pm 0.1) \times 10^7$ $M_\odot$ (Sandoval et al. 2015)

ρ **(highest):** $\sim 10^5$ $M_\odot$ pc^{-3} – M85-HCC 1 [611]

Description: Highest mean stellar density
Evaluation as true superlative: ? – Observational selection could make it difficult to identify still denser clusters, as they would appear stellar on images (c.f., Sandoval et al. 2015).

M85-HCC 1 *is sidereal source*
M85-HCC 1 designation in Simbad: [SVR2015] M85-HCC1
Reason for selection of M85-HCC 1: Explicit superlative
Notes on M85-HCC 1: Mass: $(1.2 \pm 0.1) \times 10^7$ $M_\odot$; effective radius: 1.85 ± 0.9 pc; mass surface density: 5.8×10^5 $M_\odot$ pc^{-2}
Works where M85-HCC 1 referred to as superlative: Sandoval et al. (2015)
References for data on M85-HCC 1: Sandoval et al. (2015)
Works on M85-HCC 1's host: Tully et al. (2013)
Relationships between M85-HCC 1 and other Exotica Catalog objects: Within the sky region occupied by: Virgo Cluster [506]

M_V **(dimmest):** 0.7 ± 0.3 – Kim 3 [612]

Description: Highest V-band absolute magnitude (lowest V-band luminosity)
Evaluation as true superlative: ✕ ? – Fainter globular clusters would be very difficult to detect, and we know no particular reason to expect surveys have reached the tail of the luminosity (or mass) distribution.

Kim 3 *is sidereal source*
Reason for selection of Kim 3: Explicit superlative
Notes on Kim 3: Effective radius: $2.29^{+1.28}_{-0.52}$ pc

Works where Kim 3 referred to as superlative: Kim et al. (2016)
References for data on Kim 3: Kim et al. (2016)

***t* (oldest):** ∼ 12.5–13.0 Gyr – NGC 6522 [613]

Description: Globular cluster with greatest age as observed
Evaluation as true superlative: ✓ – Approaches age of Universe

NGC 6522 *is sidereal source*
Reason for selection of NGC 6522: Explicit superlative
Works where NGC 6522 referred to as superlative: Barbuy et al. (2009); Kerber et al. (2018)
References for data on NGC 6522: Kerber et al. (2018)

Alternative superlative object(s): NGC 6626 – about same age as NGC 6522 (Kerber et al. 2018); NGC 6362 – about same age as NGC 6522 (Kerber et al. 2018)

[Fe/H] (poorest): $-2.48^{+0.06}_{-0.11}$ – ESO 280-SC06 [614]

Description: Lowest mean iron abundance (and possibly metallicity)
Evaluation as true superlative: L – Constrained by observations of Local Group globular clusters, which suggest a metallicity floor.

ESO 280-SC06 *is sidereal source*
ESO 280-SC06 designation in Simbad: ESO 280-6
Reason for selection of ESO 280-SC06: Explicit superlative in Milky Way
Notes on ESO 280-SC06: (Simpson 2018) proposes a [Fe/H] floor of -2.50 in the Local Group; Beasley et al. (2019) find the lower limit of -2.5 applies generally, at least when [Fe/H] is known precisely
Works where ESO 280-SC06 referred to as superlative: Simpson (2018)
References for data on ESO 280-SC06: Simpson (2018)

Alternative superlative object(s): Caldwell et al. (2011) lists three in M31 with [Fe/H] ¡ -2.5 (B157-G212: -2.6 ± 0.3, B462: -2.6 ± 0.3, B160-G214: -2.8 ± 0.3), but all have wide error bars

[Fe/H] (richest): ∼ −0.2–0.2 – NGC 6528 [615]

Description: Highest mean iron abundance (and possibly metallicity)
Evaluation as true superlative: M – Constrained by observations of Milky Way globular clusters. Possibly limited by the Milky Way's chemical evolution?

NGC 6528 *is sidereal source*
Reason for selection of NGC 6528: Explicit possible superlative in Milky Way
Notes on NGC 6528: [Fe/H]: 0.07 ± 0.01 (Carretta et al. 2001), -0.17 ± 0.01 (Origlia et al. 2005), +0.2 (Lagioia et al. 2014), $+0.04 \pm 0.02$ (Liu et al. 2017), -0.14 ± 0.06 (Muñoz et al. 2018)
Works where NGC 6528 referred to as superlative: Lagioia et al. (2014); Muñoz et al. (2018)
References for data on NGC 6528: Lagioia et al. (2014); Muñoz et al. (2018)

Alternative superlative object(s): Bol 112 – M31 globular cluster, [Fe/H]: 0.3 ± 0.1 (Caldwell et al. 2011); Bol 169 – M31 globular cluster, [Fe/H]: 0.3 ± 0.1 (Caldwell et al. 2011)

2.8 ISM

2.8.1 All ISM

T (coldest): 0.3–2 K – Boomerang Nebula [616]

Description: Coldest temperature gas
Evaluation as true superlative: ✓ – Near absolute zero and cooler than cosmic microwave background, allowed only under special circumstances.

Boomerang Nebula *is sidereal source*
Reason for selection of Boomerang Nebula: Explicit superlative

Caveats about selection of Boomerang Nebula: Dust temperature probably higher (Sahai et al. 2017)
Notes on Boomerang Nebula: Gas temperature: ~ 0.3–1 K, definitely colder than CMB (Sahai & Nyman 1997), 2 K (Bohigas 2017)
Works where Boomerang Nebula referred to as superlative: Sahai & Nyman (1997); Sahai et al. (2017)
References for data on Boomerang Nebula: Sahai & Nyman (1997); Bohigas (2017)

2.8.2 Giant molecular clouds

M (largest, Galactic): 8×10^6 $M_\odot$ – Sgr B2 [617]

Description: Highest gas mass of Milky Way giant molecular clouds
Evaluation as true superlative: M (R) – Constrained by observations of Milky Way molecular ISM. More massive molecular clouds would be brighter in molecular lines and easier to detect. (More massive molecular clouds may exist in starbursts and high-redshift galaxies, where mean gas densities are higher and ISM turbulence is different.)

Sgr B2 *is sidereal source*
Reason for selection of Sgr B2: Explicit possible superlative
Notes on Sgr B2: Mass: 6×10^6 $M_\odot$ (Goldsmith et al. 1990), 8×10^6 $M_\odot$ (Schmiedeke et al. 2016); distance assumed to be identical to Sgr A* (8,178 pc) (Gravity Collaboration et al. 2019b)
Works where Sgr B2 referred to as superlative: Schmiedeke et al. (2016); Sánchez-Monge et al. (2017)
References for data on Sgr B2: Schmiedeke et al. (2016)
Relationships between Sgr B2 and other Exotica Catalog objects: Contains within projected sky region: Sgr B2(N) AN01 [618]

2.8.3 Hot cores

M (largest): 9,000 $M_\odot$ – Sgr B2(N) AN01 [618]

Description: Highest gas mass
Evaluation as true superlative: M – Constrained by observations of Milky Way molecular ISM. More massive molecular clouds would be brighter in molecular lines and easier to detect.

Sgr B2(N) AN01 *is sidereal source*
Sgr B2(N) AN01 designation in Simbad: Sgr B2 HII K2
Reason for selection of Sgr B2(N) AN01: Highest value we found in literature; Sgr B2(N) highest in Garay & Lizano (1999) Table 2
Notes on Sgr B2(N) AN01: Contains 73% of total mass in Sgr B2(N), which is itself sometimes referred to as hot core; distance assumed to be identical to Sgr A* (8,178 pc) (Gravity Collaboration et al. 2019b)
References for data on Sgr B2(N) AN01: Sánchez-Monge et al. (2017)
Relationships between Sgr B2(N) AN01 and other Exotica Catalog objects: Within the sky region occupied by: Sgr B2 [617]

2.8.4 HII regions

$L_{H\alpha}$ (brightest): $(1.3\text{–}3.9) \times 10^6$ $L_\odot$ – 30 Dor [619]

Description: Highest luminosity in Hα line
Evaluation as true superlative: ✕/L – Constrained by observations of Local Group. These HII regions are extremely easy to detect and any brighter ones should have been found. Even more extreme objects are known to exist outside the Local Group, although they are more difficult to study.

30 Dor *is sidereal source*
30 Dor designation in Simbad: 30 Dor Nebula
30 Dor also known as: Tarantula Nebula
Reason for selection of 30 Dor: Explicit Local Group superlative
Notes on 30 Dor: Roughly equivalent to highest stellar mass and total luminosity; Hα luminosity: $\sim 1.3(d/50\text{ kpc})^2 \times 10^6$ $L_\odot$ for $30'$ aperture (Kennicutt & Hodge 1986), 3.9×10^6 $L_\odot$ (Crowther 2019); radius: 100 pc (Sabbi et al. 2013), 185 pc (Crowther 2019); ionizing photon output: 1.2×10^{52} s^{-1}, bolometric luminosity: 2.5×10^8 $L_\odot$ (Crowther 2019)
Works where 30 Dor referred to as superlative: Relaño & Kennicutt (2009); Sabbi et al. (2013); Crowther (2019)

References for data on 30 Dor: Relaño & Kennicutt (2009); Crowther (2019)
Works on 30 Dor's host: Pietrzyński et al. (2019)
Relationships between 30 Dor and other Exotica Catalog objects: Contains within projected sky region: Melnick 34 [600], R136 a1 [566]; Adjacent on sky to (sharing parent object with): CAL 83 nebula [382], NS 1987A [592], OGLE LMC-CEP-4506 [702], PSR J0537-6910 [586], SN 1987A [375]
Relationships between 30 Dor and objects in I17: Within the sky region occupied by: LMC

Alternative superlative object(s): II Zw 40 supernebula – giant HII region in Blue Compact Dwarf galaxy, $L_{H\alpha} \approx 3 \times 10^7\ L_\odot$ (Vanzi et al. 2008), ionizing photon output: $4.7 \times 10^{52}\ s^{-1}$ (Kepley et al. 2014), $6 \times 10^{52}\ s^{-1}$ (Leitherer et al. 2018), bolometric lumiosity: $1.3 \times 10^9\ L_\odot$ (Leitherer et al. 2018)

R (biggest): ~ 200 pc – NGC 604 [347]

Description: Largest radius
Evaluation as true superlative: ✗/L – Constrained by observations of Local Group. A Strömgren sphere estimate implies an even brighter cluster than NGC 604 or 30 Dor would be needed to ionize an even larger region in ISM conditions typically found in local star-forming galaxies. Such clusters exist in starburst regions.

NGC 604 *is sidereal source*
Reason for selection of NGC 604: Explicit Local Group superlative, sometimes second to 30 Dor
Notes on NGC 604: Radius: ~ 100 pc (core) – ~ 200 pc (halo) (Melnick 1980), 245 pc (Yang et al. 1996), 200–400 pc (Tachihara et al. 2018), 200 pc (Crowther 2019); Hα luminosity: $1.2 \times 10^6\ L_\odot$ (Crowther 2019)
Works where NGC 604 referred to as superlative: Maíz-Apellániz et al. (2004); Tachihara et al. (2018)
References for data on NGC 604: Melnick (1980); Crowther (2019)
Other works on NGC 604: Maíz-Apellániz et al. (2004); Hunter et al. (1996)
Relationships between NGC 604 and objects in I17: Within the sky region occupied by: M33

Alternative superlative object(s): II Zw 40 supernebula – giant HII region in Blue Compact Dwarf galaxy, radius 200 pc (Vanzi et al. 2008)

2.8.5 Maser regions

EIRP$_{H_2O}$ (brightest, Galactic): $\sim 1\ L_\odot$ – W49N [620]

Description: Highest apparent isotropic luminosity in 22 GHz water line
Evaluation as true superlative: M (N) – Constrained by observations of Milky Way. Brighter Galactic masers would be even easier to detect and should have been found, unless they are transient. (Water "kilomasers" associated with star-forming regions are found in other galaxies, and megamasers are found in AGNs.)

W49N *is sidereal source*
Reason for selection of W49N: Explicit superlative
Notes on W49N: Maser luminosity variable, total EIRP fluctuated from 0.3–0.8 $L_\odot$ in the 1960s–1980s (Liljestrom et al. 1989)
Works where W49N referred to as superlative: Lo (2005); Darling et al. (2008); Zhang et al. (2013); Shakhvorostova et al. (2020)
References for data on W49N: Lo (2005); Darling et al. (2008); Zhang et al. (2013); Shakhvorostova et al. (2020)

2.9 Galaxies

2.9.1 All galaxies

M$_{1/2}$ (smallest): $< 1.5 \times 10^5\ M_\odot$ – Segue 2 [621]

Description: Smallest mass, including dark matter, within (three dimensional) half-light radius
Evaluation as true superlative: ✗ – Small dark matter halos are expected to be dominant in numbers by far, but would be very difficult to detect because they have few (or no) stars (e.g., Tollerud et al. 2008; see also Moore et al. 1999).

Segue 2 *is sidereal source*
Reason for selection of Segue 2: Explicit superlative

Works where Segue 2 referred to as superlative: Kirby et al. (2013)
References for data on Segue 2: Kirby et al. (2013)

$M_\star$ (smallest): 600^{+115}_{-105}–$1{,}300^{+200}_{-200}$ $M_\odot$ – Segue 1 [622]

Description: Smallest stellar mass
Evaluation as true superlative: ✗ – Ultrafaint galaxies with few stars are expected to be dominant in numbers, probably to arbitrarily small stellar masses, but their faintness makes them difficult to detect (e.g., Tollerud et al. 2008).

Segue 1 *is sidereal source*
Reason for selection of Segue 1: Explicit superlative in stellar luminosity, which traces stellar mass
Notes on Segue 1: Different mass estimates based on different assumed initial mass functions (Martin et al. 2008)
Works where Segue 1 referred to as superlative: Geha et al. (2009); Simon et al. (2011)
References for data on Segue 1: Martin et al. (2008)
Other works on Segue 1: Simon et al. (2011); Simon (2019); Geha et al. (2009); Martin et al. (2008)

Alternative superlative object(s): SDSS J1058+2843 – stellar mass: 210^{+75}_{-60}–400^{+145}_{-120} $M_\odot$, status as galaxy unclear (Martin et al. 2008)

$M_\star$ (largest): $(1–4) \times 10^{12}$ $L_\odot$ – IC 1101 [623]; $(2–6) \times 10^{12}$ $M_\odot$ – OGC 21 [624]

Description: Largest stellar mass
Evaluation as true superlative: ✓ – At observed tail of mass distribution, and much more massive galaxies would be brighter and easier to detect. The cosmic history of mass accretion limits the mass of galaxies. Arguably, as virialized dark matter halos, galaxy clusters as a whole (or at least their intracluster stars) might be considered as enormous galaxies, but they usually are not classified so (see discussion in Willman & Strader 2012).

IC 1101 *is sidereal source*
IC 1101 also known as: Abell 2029 BCG
Reason for selection of IC 1101: Among largest masses we found in literature
Notes on IC 1101: M_K: -27.52 (Loubser & Sánchez-Blázquez 2011); stellar mass: 3.7×10^{12} $M_\odot$ (Loubser & Sánchez-Blázquez 2011, applying Cappellari 2013 conversion from M_K), $(1.1–1.5) \times 10^{12}$ $M_\odot$ (Dullo et al. 2017)
References for data on IC 1101: Loubser & Sánchez-Blázquez (2011); Dullo et al. (2017)
Other works on IC 1101: Hagen et al. (2016); Uson et al. (1991); Dullo et al. (2017)

OGC 21 *is sidereal source*
OGC 21 designation in Simbad: 2MASX J12220526+4518109
OGC 21 also known as: 2MASX J12220526+4518109
Reason for selection of OGC 21: Among largest masses we found in literature; brightest r-band luminosity in Ogle et al. (2019) catalog of superluminous galaxies
Notes on OGC 21: M_K: -27.96 (Simbad); Stellar mass: 5.7×10^{12} $M_\odot$ (from M_K and Cappellari 2013 conversion), Ogle et al. (2019) implies all galaxies in their catalog have $M_\star \leq 2 \times 10^{12}$ $M_\odot$
References for data on OGC 21: Ogle et al. (2019)

Alternative superlative object(s): A3558-BCG – stellar mass: 6.9×10^{12} $M_\odot$ (Dullo 2019), 7.1×10^{11} $M_\odot$ (Di Gennaro et al. 2018)

R_{max} (biggest): 610 kpc – IC 1101 [623]; 960 kpc – LEDA 088678 [625]

Description: Largest radius to which associated stellar population has been measured
Evaluation as true superlative: ✓ – Limited by environment (galaxy interactions in clusters, lack of material in field). Arguably, as virialized dark matter halos, galaxy clusters as a whole (or at least their intracluster stars) might be considered as enormous galaxies, but they usually are not classified so (see discussion in Willman & Strader 2012).

IC 1101 *is sidereal source*
IC 1101 also known as: Abell 2029 BCG
Reason for selection of IC 1101: Explicit possible superlative; among largest values we found in literature
Notes on IC 1101: Surface brightness follows de Vaucouleurs profile out $607(h/0.7)^{-1}$ kpc (Uson et al. 1991); 2MASS total radius: 49.4 ″ (Skrutskie et al. 2006), 62.8 kpc (with NED angular scale)

Works where IC 1101 referred to as superlative: Uson et al. (1991); Hagen et al. (2016)
References for data on IC 1101: Uson et al. (1991); Hagen et al. (2016)
Other works on IC 1101: Uson et al. (1991); Dullo et al. (2017); Loubser & Sánchez-Blázquez (2011)

LEDA 088678 *is sidereal source*
LEDA 088678 designation in Simbad: LEDA 88678
LEDA 088678 also known as: Abell 1651 BCG
Reason for selection of LEDA 088678: Among largest values we found in literature
Notes on LEDA 088678: Surface brightness follows de Vaucouleurs profile out $957(h/0.7)^{-1}$ kpc (Gonzalez et al. 2000); 2MASS total radius: 39.0 ″ (Skrutskie et al. 2006), 68.5 kpc (with NED angular scale)

$R_{\rm eff}$ (biggest): $\lesssim$ 146–439 kpc – IC 1101 [623]

Description: Largest half-light radius for galaxy
Evaluation as true superlative: ✓ – Limited by environment (galaxy interactions in clusters, lack of material in field). Arguably, as virialized dark matter halos, galaxy clusters as a whole (or at least their intracluster stars) might be considered as enormous galaxies, but they usually are not classified so (see discussion in Willman & Strader 2012).

IC 1101 *is sidereal source*
IC 1101 also known as: Abell 2029 BCG
Reason for selection of IC 1101: Among largest values we found in literature; third largest significant measurement of Donzelli et al. (2011) and Kluge et al. (2020)
Notes on IC 1101: Effective radius: 439 kpc (Donzelli et al. 2011); 146 kpc (stellar halo, from 87.1 kpc exponential scale length; contains 57.5% of brightness), with minority of light from spheroidal component (25.1%) with $R_{\rm eff} = 8.0$ kpc and intermediate component (17.4%) with $R_{\rm eff} = 29.4$ kpc (Dullo et al. 2017); 329 ± 82 kpc (Kluge et al. 2020).
Other works on IC 1101: Hagen et al. (2016); Uson et al. (1991); Dullo et al. (2017); Loubser & Sánchez-Blázquez (2011)

Alternative superlative object(s): NGC 6173: effective radius: $1{,}073.1 \pm 296.8$ kpc (Seigar et al. 2007; unclear verification status); UGC 240 (=Abell 401 BCG): effective radius: 969 kpc (Donzelli et al. 2011; unclear verification status); NGC 7647 (=Abell 2589 BCG) – effective radius: 726 kpc (Donzelli et al. 2011; unclear verification status); 2MASX J23554260+1120355 (=Abell 2675 BCG): 430 ± 69 kpc (Kluge et al. 2020; unclear verification status); 2MASX J06124115+4835445 (=Abell 553 BCG): 405 ± 47 kpc (Kluge et al. 2020; unclear verification status); Holm 15A – effective radius: 66.7 kpc (Sersic profile, i-band; Mehrgan et al. 2019); Abell 1651 BCG – effective radius: 59.8 kpc (used for surface brightness profile fit; Gonzalez et al. 2000); UGC 7069 – ring galaxy, ring radius: 57.5 kpc (Ghosh & Mapelli 2008); SS 03 – 55.3 kpc (from exponential scale length of 32.98 kpc; Ogle et al. 2016)

Σ (largest): 9.4×10^{10} $M_\odot$ kpc^{-2} – M59-UCD3 [626]

Description: Largest stellar surface density
Evaluation as true superlative: ✓ – Near expected maximum surface density allowed due to feedback, $\sim 10^{11}$ $M_\odot$ kpc^{-2} (according to Hopkins et al. (2010))

M59-UCD3 *is sidereal source*
M59-UCD3 designation in Simbad: [SVR2015] M59-UCD3
Reason for selection of M59-UCD3: Explicit superlative
Works where M59-UCD3 referred to as superlative: Sandoval et al. (2015); Liu et al. (2015)
References for data on M59-UCD3: Liu et al. (2015)
Works on M59-UCD3's host: Tully et al. (2013)
Relationships between M59-UCD3 and other Exotica Catalog objects: Gravitationally bound to: M59 [392]; Within the sky region occupied by: Virgo Cluster [506]

$L_\star$ (faintest): 335^{+235}_{-185} $L_\odot$ – Segue 1 [622]

Description: Smallest stellar luminosity
Evaluation as true superlative: ✕ – Ultrafaint galaxies with few stars and low stellar luminosity are expected to be common, probably to arbitrarily small stellar luminosities, but their faintness makes them difficult to detect (e.g., Tollerud et al. 2008).

Segue 1 *is sidereal source*

Reason for selection of Segue 1: Explicit superlative
Notes on Segue 1: Luminosity is V-band; M_V: $-1.5^{+0.6}_{-0.7}$ (Martin et al. 2008)
Works where Segue 1 referred to as superlative: Geha et al. (2009); Simon et al. (2011)
References for data on Segue 1: Martin et al. (2008); Simon (2019)
Other works on Segue 1: Simon et al. (2011); Martin et al. (2008); Geha et al. (2009)

Alternative superlative object(s): SDSS J1058+2843 – M_V: $-0.2^{+1.1}_{-1.0}$; $L_\star$ (V-band): 100^{+95}_{-100} $L_\odot$, status as galaxy unclear (Martin et al. 2008)

$L_\star$ (brightest): $(3.6 \pm 0.3) \times 10^{13}$ $L_\odot$ – SPT 0346-52 [627]; $(4.9 \pm 1.0) \times 10^{13}$ $L_\odot$ – WISE J101326.25+611220.1 [628]

Description: Highest bolometric stellar luminosity (excluding luminosity contribution from AGN)
Evaluation as true superlative: ✓ – Brighter galaxies would be easy to detect with current capabilities, even at high redshift. Luminosity (and star-formation rate) is probably limited by available gas mass in galaxies and feedback.

SPT 0346-52 *is sidereal source*
SPT 0346-52 designation in Simbad: SPT-S J034640-5204.9
Reason for selection of SPT 0346-52: Among highest we found in literature; explicit superlative
Notes on SPT 0346-52: Redshift: 5.6559; magnification: 5.6 (870 μm; Spilker et al. 2016); Ma et al. (2016) found no sign of an AGN in X-rays or radio
Works where SPT 0346-52 referred to as superlative: Litke et al. (2019)
References for data on SPT 0346-52: Ma et al. (2016)
Other works on SPT 0346-52: Ma et al. (2016)

WISE J101326.25+611220.1 *is sidereal source*
Reason for selection of WISE J101326.25+611220.1: Highest we found in literature; explicit superlative for total luminosity including AGN
Notes on WISE J101326.25+611220.1: Redshift: 3.703; total infrared luminosity: $(1.62 \pm 0.08) \times 10^{14}$ $L_\odot$, AGN infrared luminosity: $(1.13 \pm 0.06) \times 10^{14}$ $L_\odot$; starburst infrared luminosity: $\sim 1.2^{+0.6}_{-0.5} \times 10^{13}$ $L_\odot$ (Toba et al. 2018), $(4.9 \pm 1.0) \times 10^{13}$ $L_\odot$ (Toba et al. 2020)
Works where WISE J101326.25+611220.1 referred to as superlative: Toba et al. (2020)
References for data on WISE J101326.25+611220.1: Toba et al. (2020)

Alternative superlative object(s): HXMM05 – total infrared luminosity: $(4 \pm 1) \times 10^{13}$ $L_\odot$ (Leung et al. 2019); W0533-3401 – starburst bolometric luminosity: $(3.6 \pm 0.4) \times 10^{13}$ $L_\odot$ (Fan et al. 2019); HATLAS 084933.4+021443 W – infrared luminosity: $(3.3 \pm 0.3) \times 10^{13}$ $L_\odot$ (Ivison et al. 2013); HFLS-3 – far-infrared luminosity: $2.86^{+0.32}_{-0.31} \times 10^{13}$ $L_\odot$ (Riechers et al. 2013)

μ_V (faintest): 31.9 mag arcsec^{-2} – Antlia 2 [629]

Description: Faintest mean V-band surface brightness
Evaluation as true superlative: ✕ – Arbitrarily faint galaxies expected to be common in dark matter cosmology; surface brightness may be further reduced by tidal effects.

Antlia 2 *is sidereal source*
Antlia 2 designation in Simbad: Antlia II Dwarf Galaxy
Reason for selection of Antlia 2: Explicit superlative
Works where Antlia 2 referred to as superlative: Torrealba et al. (2019)
References for data on Antlia 2: Torrealba et al. (2019)

[Fe/H] (poorest): -2.65 ± 0.07 – Reticulum II [630]

Description: Lowest mean stellar iron abundance
Status as true superlative unknown

Reticulum II *is sidereal source*
Reason for selection of Reticulum II: Explicit superlative

Works where Reticulum II referred to as superlative: Simon et al. (2015)
References for data on Reticulum II: Simon et al. (2015)

Alternative superlative object(s): Segue 1 – mean [Fe/H]: ~ -2.5 (Simon et al. 2011), metallicity has wide spread from -3.8 to -1.4 in measured stars (Frebel et al. 2014), whereas Reticulum I has much lower spread

z **(furthest):** $11.09^{+0.08}_{-0.12}$ – GN-z11 [631]; 10.7–11.1 – MACS0647-JD [632]

Description: Greatest redshift
Evaluation as true superlative: ✕ ? – Stars may have formed as early as $z \gtrsim 50$ and small star-forming galaxies at $z \sim 50$ (Naoz et al. 2006), but their hosts (if any) would be at such a great luminosity distance and so faint that it would be hard to detect them. Larger galaxies that form stars relatively efficiently may have only formed at $z \lesssim 15$, however (Bromm & Yoshida 2011).

GN-z11 *is sidereal source*
GN-z11 designation in Simbad: [OBI2014] GN-z10-1
Reason for selection of GN-z11: Highest value we found in literature
References for data on GN-z11: Oesch et al. (2016)

MACS0647-JD *is sidereal source*
MACS0647-JD designation in Simbad: [CZC2013] MACS0647-JD1
Reason for selection of MACS0647-JD: Explicit superlative; among highest values we found in literature
Notes on MACS0647-JD: Redshift: ~ 10.7 (photometric, Coe et al. 2013), ~ 10.8 (lensing model, Chan et al. 2017), $11.1^{+0.5}_{-0.9}$ (lensing model, Lam et al. 2019); total magnification: $13.6^{+1.2}_{-0.8}$ (Lam et al. 2019)
Works where MACS0647-JD referred to as superlative: Coe et al. (2013)
References for data on MACS0647-JD: Coe et al. (2013); Chan et al. (2017); Lam et al. (2019)

2.9.2 Quiescent galaxies

L_V **(brightest):** $\sim 1.1 \times 10^{12}$ $L_\odot$ – IC 1101 [623]

Description: Highest V-band luminosity (approximately highest stellar luminosity)
Evaluation as true superlative: ✓ – At observed tail of stellar mass distribution, and much more brighter quiescent galaxies would be easier to detect. The cosmic history of mass accretion limits the stellar mass of galaxies and thus quiescent galaxy stellar luminosity. Arguably, as virialized dark matter halos, galaxy clusters as a whole (or at least their intracluster stars) might be considered as enormous galaxies, but they usually are not classified so (see discussion in Willman & Strader 2012).

IC 1101 *is sidereal source*
Reason for selection of IC 1101: Explicit superlative
Notes on IC 1101: Dullo et al. (2017) gives $M_V = -23.8$ for the spheroid component, which accounts for 25.1% of the light, converted to total V luminosity 1.1×10^{12} $L_\odot$ with $L_V = L_\odot 10^{-0.4(M_V - M_V^\odot)}$ where $M_V^\odot = 4.81$ (Willmer 2018)
Works where IC 1101 referred to as superlative: Uson et al. (1991)
References for data on IC 1101: Dullo et al. (2017)
Other works on IC 1101: Hagen et al. (2016); Uson et al. (1991); Dullo et al. (2017); Loubser & Sánchez-Blázquez (2011)

z **(furthest):** 3.717 – ZF-COSMOS-20115 [633]

Description: Highest redshift
Status as true superlative unknown

ZF-COSMOS-20115 *is sidereal source*
ZF-COSMOS-20115 designation in Simbad: ZFOURGE COSMOS 20115
Reason for selection of ZF-COSMOS-20115: Explicit superlative; spectroscopic redshift
Notes on ZF-COSMOS-20115: SFR: < 0.2 $M_\odot$ yr^{-1} (Glazebrook et al. 2017), ~ 100 $M_\odot$ yr^{-1} (Simpson et al. 2017), 0–0.65 $M_\odot$ yr^{-1} averaged over 100 Myr (Schreiber et al. 2018)
Works where ZF-COSMOS-20115 referred to as superlative: Glazebrook et al. (2017)
References for data on ZF-COSMOS-20115: Glazebrook et al. (2017)

Alternative superlative object(s): SXDS-10017 – "tentative" spectroscopic redshift: 3.767 (Valentino et al. 2020)

2.9.3 Star-forming galaxies

SFR (highest): $3{,}600 \pm 300\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$ – SPT 0346-52 [627]

Description: Highest star-formation rate

Evaluation as true superlative: ✓ – Galaxies with a higher star-formation rate should produce more luminous, massive stars and have an overall higher bolometric luminosity. Thus they would be easy to detect with current capabilities, even at high redshift. Star-formation rate is probably limited by available gas mass in galaxies and feedback.

SPT 0346-52 *is sidereal source*

SPT 0346-52 designation in Simbad: SPT-S J034640-5204.9

Reason for selection of SPT 0346-52: Among highest values we found in literature

Notes on SPT 0346-52: Star-formation rate: $4{,}840^{+1{,}090}_{-890}\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$ (CIGALE SED fit; Ma et al. 2015, 3,830–5,340 $\mathrm{M}_\odot\ \mathrm{yr}^{-1}$ (infrared luminosity; Ma et al. 2015), $3{,}600 \pm 300\ \mathrm{M}_\odot\,\mathrm{yr}^{-1}$ (infrared luminosity; Ma et al. 2016); Litke et al. (2019) argues is actually two galaxies undergoing merger

References for data on SPT 0346-52: Ma et al. (2016)

Other works on SPT 0346-52: Ma et al. (2016); Litke et al. (2019)

Alternative superlative object(s): In general, galaxies with the highest luminosities from star formation will also have the highest star-formation rates; WISE J101326.25+611220.1 – star-formation rate: $2{,}810 \pm 360\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$ (Toba et al. 2020); HXMM05 – star-formation rate: $2{,}900^{+750}_{-595}$ (Leung et al. 2019); W0533-3401 – star-formation rate: $6{,}985 \pm 3{,}006$ (Fan et al. 2019); HATLAS 084933.4+021443 W – star-formation rate: 3,400 (Ivison et al. 2013); HFLS-3 – star-formation rate: 2,900 (Riechers et al. 2013)

$\mathbf{R_{eff}}$ (smallest): $\sim 166 \pm 54$ pc – POX 186 [432]

Description: Star-forming galaxy with smallest half-light radius

Status as true superlative unknown

POX 186 *is sidereal source*

Reason for selection of POX 186: Explict superlative; smallest value we found in literature

Notes on POX 186: Calculated from V-band scale length 99 ± 32 pc, where $\mathrm{R_{eff}}$ is 1.68 scale lengths; I-band scale length 120 ± 21 pc

Works where POX 186 referred to as superlative: Doublier et al. (2000)

References for data on POX 186: Guseva et al. (2004)

Other works on POX 186: Doublier et al. (2000); Corbin et al. (2006); Guseva et al. (2004)

$\mathbf{M_{gas}/M_\star}$ (largest): 35–475 – AGC 229385 [634]

Description: Highest ratio of gas mass to stellar mass

Evaluation as true superlative: ✕ ? – Plausible existence of dark galaxies with no stars and $\mathrm{M_{gas}/M_\star} = \infty$.

AGC 229385 *is sidereal source*

AGC 229385 designation in Simbad: Coma P

Reason for selection of AGC 229385: Among highest values we found in literature

Notes on AGC 229385: HI-to-stellar mass ratio: > 320 and ~ 475 (Janowiecki et al. 2015), 35 (Ball et al. 2018), 81 (Brunker et al. 2019); Brunker et al. (2019) notes the ratio is extreme

References for data on AGC 229385: Janowiecki et al. (2015); Brunker et al. (2019)

Other works on AGC 229385: Anand et al. (2018b)

Relationships between AGC 229385 and other Exotica Catalog objects: Within the sky region occupied by: HI 1232+20 [443]

12 + log O/H (poorest): 6.98 ± 0.02 – J0811+4730 [635]

Description: Poorest ISM oxygen abundance (presumably among lowest metallicities)

Evaluation as true superlative: R? – Constrained by observations of local Universe; existence of any metal poorer galaxies (at least at $z \sim 0$) unclear

J0811+4730 *is sidereal source*

J0811+4730 designation in Simbad: SDSS J081152.12+473026.2

Reason for selection of J0811+4730: Explicit superlative
Works where J0811+4730 referred to as superlative: Izotov et al. (2018)
References for data on J0811+4730: Izotov et al. (2018)

Alternative superlative object(s): SBS 0335-052W – mean 12 + log O/H: 7.12 ± 0.03, former superlative (Izotov et al. 2005), in one HII region 6.86 ± 0.14 (Izotov et al. 2009)

12 + log O/H (richest): 8.54–9.21 – NGC 2841 [636]

Description: Richest ISM oxygen abundance
Evaluation as true superlative: R? – Constrained by observations of local Universe. Theoretically limited by chemical evolution of galaxies. Most metal-rich galaxies have high stellar masses and thus are easy to find.

NGC 2841 *is sidereal source*
Reason for selection of NGC 2841: Consistently high ranking in oxygen abundance determinations listed in De Vis et al. (2019), among highest we found in literature
Notes on NGC 2841: Oxygen abundance characteristic of disk, center has higher metallicity
References for data on NGC 2841: Moustakas et al. (2010); De Vis et al. (2019)

$\mathrm{EIRP}_{\mathrm{OH}}$ (brightest): 13,000 $L_\odot$ – IRAS 14070+0525 [637]

Description: Brightest apparent isotropic OH maser luminosity, summed over the entire galaxy
Evaluation as true superlative: ✓ – Brighter OH masers would be easy to detect. Luminosity probably limited by available radiation energy density to pump maser regions, in turn limited by stellar surface density.

IRAS 14070+0525 *is sidereal source*
IRAS 14070+0525 designation in Simbad: [DG2000] 14070+0525
Reason for selection of IRAS 14070+0525: Explicit superlative
Notes on IRAS 14070+0525: Maser emission mostly resolved out by VLBA and thus spread out over scales > 325 pc, no sign of AGN (Pihlström et al. 2005)
Works where IRAS 14070+0525 referred to as superlative: Baan et al. (1992); Pihlström et al. (2005)
References for data on IRAS 14070+0525: Pihlström et al. (2005)

2.9.4 Spiral galaxies

$M_\star$ (largest): $\sim 1.4 \times 10^{12}$ $M_\odot$ – SS 14 [638]

Description: Largest stellar mass
Evaluation as true superlative: ✓? – Constrained by observations of galaxies in local Universe; more massive spiral galaxies should be brighter and easier to find.

SS 14 *is sidereal source*
SS 14 designation in Simbad: SDSS J095727.02+083501.7
SS 14 also known as: SDSS J095727.02+083501.7
Reason for selection of SS 14: Highest listed in Ogle et al. (2016) catalog of super spiral galaxies
Notes on SS 14: Stellar mass: 3.4×10^{11} $M_\odot$ (Ogle et al. 2016), according to Ogle et al. (2019) this must be corrected by a factor ~ 4
References for data on SS 14: Ogle et al. (2016)

Alternative superlative object(s): OGC 1549 – stellar mass: 1.02×10^{12} $M_\odot$ (Ogle et al. 2019)

R_{max} (largest): 67 kpc – SS 03 [639]

Description: Largest radius to which associated stellar population has been measured
Evaluation as true superlative: ✓? – Constrained by observations of galaxies in local Universe

SS 03 *is sidereal source*
SS 03 designation in Simbad: 2MASX J16394598+4609058
SS 03 also known as: 2MASX J16394598+4609058
Reason for selection of SS 03: Explicit superlative

Works where SS 03 referred to as superlative: Ogle et al. (2016)
References for data on SS 03: Ogle et al. (2016)

z **(furthest):** 2.54 – A1689B11 [640]

Description: Highest redshift with a clear spiral pattern
Status as true superlative unknown

A1689B11 *is sidereal source*
A1689B11 designation in Simbad: [BBC2005] Source 11
Reason for selection of A1689B11: Explicit superlative
Notes on A1689B11: Magnification: 7.2; star-formation rate: 22 ± 2 $M_\odot$ yr^{-1}; stellar mass: $10^(9.8 \pm 0.3)$ $M_\odot$; effective radius: 2.6 ± 0.7 kpc; low velocity dispersions in disk (Yuan et al. 2017)
Works where A1689B11 referred to as superlative: Yuan et al. (2017)
References for data on A1689B11: Yuan et al. (2017)

2.9.5 Lensed galaxies

$\mathcal{M}$ **(greatest):** (60–65) $\pm$ 20 – SPT-CLJ2344-4243 Arc [641]; $\sim 80 \pm 10$ – The Snake [642]

Description: Highest average magnification (amplification or luminosity boost) summed over all images by a gravitational lens (equivalent to highest luminosity boost)
Evaluation as true superlative: ✓ – Magnification varies strongly near gravitational lens caustics, so size of galaxies limits average magnification (Kelly et al. 2018).
Caveats about superlative category: Magnifications peak along narrow caustic curves on sky, and thus is frequently highly variable over galaxy; generally not expected to be $\gtrsim 50$ because galaxy is extended object; microlensing by individual stars in lens can boost magnification by a factor of thousands (Kelly et al. 2018; Diego 2019)

SPT-CLJ2344-4243 Arc *is sidereal source*
Reason for selection of SPT-CLJ2344-4243 Arc: Among highest we found in literature
Notes on SPT-CLJ2344-4243 Arc: Mean magnification depends on aperture; lensed X-ray image detected
References for data on SPT-CLJ2344-4243 Arc: Bayliss et al. (2020)
Relationships between SPT-CLJ2344-4243 Arc and other Exotica Catalog objects: Gravitationally lensed by: Phoenix Cluster [660]

The Snake *is sidereal source*
The Snake designation in Simbad: [ZRN2012] 1.1
The Snake also known as: MACS J1206.2-0847 Giant Arc
Reason for selection of The Snake: Explicit possible superlative; among highest we found in literature
Notes on The Snake: Magnification: 80 ± 10 (Ebeling et al. 2009), ranges over different regions and images from $\sim$ 3–450 where highest magnification regions are ~ 50 pc across (Cava et al. 2018)
Works where The Snake referred to as superlative: Ebeling et al. (2009)
References for data on The Snake: Ebeling et al. (2009)

Alternative superlative object(s): Sunburst Arc (=PSZ1 G311.65-18.48) – magnification unknown, but Dahle et al. (2016) suggests it is $\gtrsim 50$ and could be ~ 100

2.10 Active galactic nuclei

2.10.1 All AGNs

$\mathbf{M}_{\mathrm{SMBH}}$ **(smallest):** 5×10^4 $M_\odot$ – RGG 118 [643]

Description: Smallest central black hole in a galaxy
Evaluation as true superlative: ? – Smaller black holes would probably be found in bulgeless dwarf galaxies (Greene et al. 2019). Theories predict that SMBHs formed from IMBH seeds – which can be as small as 100 $M_\odot$ stellar remnants (Madau & Rees 2001) or as large as 10^6 $M_\odot$ objects formed from the direct collapse of a large gas structure (e.g., Begelman et al. 2006b)

– and these could migrate to the centers of galaxies. Neither the initial mass of the seeds, their current mass, nor even if they are found in the centers of (dwarf) galaxies. If they do exist, they could be difficult to detect.

RGG 118 *is sidereal source*
RGG 118 designation in Simbad: [RGG2013] 118
Reason for selection of RGG 118: Explicit superlative
Works where RGG 118 referred to as superlative: Baldassare et al. (2015)
References for data on RGG 118: Baldassare et al. (2015)

Alternative superlative object(s): ESO 249-49 HLX-1 – may be smaller, black hole mass: 6,300–191,700 $M_\odot$ (Straub et al. 2014)

M_{SMBH} (largest): $(4.0 \pm 0.8) \times 10^{10}$ $M_\odot$ – Holm 15A [644]; $(4\text{–}10) \times 10^{10}$ $M_\odot$ – IC 1101 [623]

Description: Largest central black hole in a galaxy
Evaluation as true superlative: ✓? – Larger black holes could power bright AGNs that should be easy to detect, but measurements of mass often imprecise. Possible theoretical limit of supermassive black hole mass $\sim 10^{11}$ $M_\odot$ (King 2016; Inayoshi & Haiman 2016).

Holm 15A *is sidereal source*
Holm 15A designation in Simbad: MCG-02-02-086
Reason for selection of Holm 15A: Explicit superlative
Caveats about selection of Holm 15A: The existence of a large core carved out by an ultramassive black hole in Holm 15A has been disputed by some (Bonfini et al. 2015; Madrid & Donzelli 2016)
Notes on Holm 15A: Black hole mass: $(0.2\text{–}30) \times 10^{10}$ $M_\odot$ (López-Cruz et al. 2014), $(4.0 \pm 0.8) \times 10^{10}$ $M_\odot$ (Mehrgan et al. 2019)
Works where Holm 15A referred to as superlative: Mehrgan et al. (2019)
References for data on Holm 15A: Mehrgan et al. (2019)

IC 1101 *is sidereal source*
Reason for selection of IC 1101: Among highest values we found in literature
References for data on IC 1101: Dullo et al. (2017)
Other works on IC 1101: Hagen et al. (2016); Uson et al. (1991); Dullo et al. (2017); Loubser & Sánchez-Blázquez (2011)

Alternative superlative object(s): Ton 618: has been claimed to be the most massive known black hole, at $10^{10.82}$ $M_\odot$ – this is based on a single measurement based on an empirical correlation between 5,100 Åluminosity and Hβ line width in Shemmer et al. (2004) and is not commented upon, Ge et al. (2019) uses the same method to find $10^{10.610}$ $M_\odot$; S5 0014+083 – black hole mass: $\sim 4 \times 10^{10}$ $M_\odot$ (Ghisellini et al. 2009); $\sim (0.7\text{–}1) \times 10^{10}$ $M_\odot$ (Sbarrato et al. 2016); $\sim (0.3\text{–}1.3) \times 10^{10}$ $M_\odot$ (Campitiello et al. 2018)

L (brightest): 8.5×10^{14} $L_\odot$ – HS 1946+7658 [645]; 6.95×10^{14} $L_\odot$ – SMSS 2157-36 [646]

Description: Largest bolometric luminosity
Evaluation as true superlative: ✓ – Much brighter galaxies are easier to detect and should have been found.

HS 1946+7658 *is sidereal source*
Reason for selection of HS 1946+7658: Explicit superlative
Notes on HS 1946+7658: Optical luminosity; Hagen et al. (1992) claims the actual luminosity could be $\sim 1.5 \times 10^{15}$ $L_\odot$
Works where HS 1946+7658 referred to as superlative: Hagen et al. (1992)
References for data on HS 1946+7658: Hagen et al. (1992)

SMSS 2157-36 *is sidereal source*
SMSS 2157-36 designation in Simbad: 2MASS J21572822-3602151
Reason for selection of SMSS 2157-36: Explicit superlative
Works where SMSS 2157-36 referred to as superlative: Wolf et al. (2018)
References for data on SMSS 2157-36: Wolf et al. (2018)

L_{IR} (brightest): $(1.2\text{–}3.6) \times 10^{14}$ $L_\odot$ – WISE 2246-0526 [647]

Description: Largest infrared luminosity

Evaluation as true superlative: ✓ – Much brighter galaxies are easier to detect and should have been found, especially since WISE is all sky survey.

WISE 2246-0526 *is sidereal source*
WISE 2246-0526 designation in Simbad: WISE J224607.55-052634.9
Reason for selection of WISE 2246-0526: Explicit superlative
Notes on WISE 2246-0526: IR luminosity: 2.21×10^{14} $L_\odot$ (Tsai et al. 2015), revised down to 1.2×10^{14} $L_\odot$ by Fan et al. (2018) who claimed foreground contamination, low foreground contamination claimed by Tsai et al. (2018); bolometric luminosity: 3.49×10^{14} $L_\odot$ (Tsai et al. 2015), 3.6×10^{14} $L_\odot$ (Tsai et al. 2018)
Works where WISE 2246-0526 referred to as superlative: Tsai et al. (2015)
References for data on WISE 2246-0526: Fan et al. (2018); Tsai et al. (2018)

$M_{\star_{\rm host}}$ (smallest): $(1.2 \pm 0.4) \times 10^8$ $M_\odot$ – M60-UCD1 [648]; $\sim 2 \times 10^8$ $M_\odot$ – J1329+3234 [649]

Description: Smallest stellar mass for host galaxy known to host central black hole
Evaluation as true superlative: ✕ – Smaller galaxies with smaller central black holes should have less luminous AGNs (if any) and would be hard to detect

M60-UCD1 *is sidereal source*
Reason for selection of M60-UCD1: Explicit superlative
Notes on M60-UCD1: Likely the tidally-stripped nucleus of a formerly much larger galaxy
Works where M60-UCD1 referred to as superlative: Seth et al. (2014)
References for data on M60-UCD1: Seth et al. (2014)
Other works on M60-UCD1: Seth et al. (2014)
Works on M60-UCD1's host: Lee & Jang (2017)
Relationships between M60-UCD1 and other Exotica Catalog objects: Within the sky region occupied by: Virgo Cluster [506]
Relationships between M60-UCD1 and objects in I17: Gravitationally bound to: M60

J1329+3234 *is sidereal source*
J1329+3234 designation in Simbad: SDSS J132932.41+323417.0
Reason for selection of J1329+3234: Explicit possible superlative; among lowest we found in literature
Notes on J1329+3234: Dwarf irregular galaxy, not UCD or other likely remnant of tidal stripping
Works where J1329+3234 referred to as superlative: Secrest et al. (2015)
References for data on J1329+3234: Secrest et al. (2015)

$M_{\rm SMBH}/M_{\star_{\rm host}}$ (largest): $0.175^{+0.26}_{-0.088}$ – M60-UCD1 [648]

Description: Largest ratio of central black hole mass and host galaxy stellar mass
Evaluation as true superlative: ? – Possibility of tight star clusters bound to recoiling SMBHs, although these could be off-center or even outside the host galaxy (Merritt et al. 2009).

M60-UCD1 *is sidereal source*
Reason for selection of M60-UCD1: Among largest we found in literature
Notes on M60-UCD1: M60-UCD1 is likely the tidally-stripped nucleus of a formerly much larger galaxy, accounting for the huge ratio
References for data on M60-UCD1: Seth et al. (2014)
Other works on M60-UCD1: Seth et al. (2014)
Relationships between M60-UCD1 and other Exotica Catalog objects: Within the sky region occupied by: Virgo Cluster [506]
Relationships between M60-UCD1 and objects in I17: Gravitationally bound to: M60

Alternative superlative object(s): M59-cO – $M_{\rm SMBH}/M_{\star_{\rm host}}$: ~ 0.18 (Ahn et al. 2017)

z (furthest): 7.54 – J1342+0928 [650]

Description: Highest redshift AGN
Status as true superlative unknown

J1342+0928 *is sidereal source*
J1342+0928 designation in Simbad: ULAS J134208.10+092838.6

J1342+0928 also known as: ULAS J134208.10+092838.6
Reason for selection of J1342+0928: Explicit superlative
Works where J1342+0928 referred to as superlative: Bañados et al. (2018)
References for data on J1342+0928: Bañados et al. (2018)

2.10.2 Lensed AGNs

$\mathcal{M}$ **(greatest):** ~ 173 – CLASH B1938+666 [651]; ~ 159 – COSMOS 5921+0638 [652]

Description: Largest time-averaged magnification (luminosity boost) of an AGN by a gravitational lens
Evaluation as true superlative: ✓? – Magnification varies strongly near gravitational lens caustics, so size of AGN could limit average magnification.
Caveats about superlative category: Magnifications peak along narrow caustic curves on sky, and thus can vary over different emission regions of the AGN radiating different parts of its spectrum (chromatic magnification) (Stacey et al. 2018); microlensing in lensing source can cause magnification to fluctuate

CLASH B1938+666 *is sidereal source*
CLASH B1938+666 designation in Simbad: BWE 1938+6641
Reason for selection of CLASH B1938+666: Among highest values we found in literature
Caveats about selection of CLASH B1938+666: Barvainis & Ivison (2002) calculate this submillimeter magnification but largely disregard it in their work
Notes on CLASH B1938+666: Host galaxy has NIR magnification of ~ 13 (Lagattuta et al. 2012)

COSMOS 5921+0638 *is sidereal source*
COSMOS 5921+0638 designation in Simbad: [FKC2008] COSMOS 5921+0638
Reason for selection of COSMOS 5921+0638: Among highest values we found in literature
Notes on COSMOS 5921+0638: Sum of magnifications of four images in Table 9 of Anguita et al. (2009), who otherwise report a total magnification of ~ 150
References for data on COSMOS 5921+0638: Anguita et al. (2009)

Alternative superlative object(s): SDSS J010013.02+280225.8 – Fujimoto et al. (2020) invoke $\mathcal{M} \sim 450$ to explain the $z > 6$ quasar's apparent high luminosity, but Pacucci & Loeb (2020) believes that is implausible

2.10.3 Radio lobes

D **(largest):** 4.7 Mpc – J1420-0545 [653]

Description: Highest end-to-end length of radio lobe pair
Evaluation as true superlative: ✓ – Constrained by radio surveys of local Universe.

J1420-0545 *is sidereal source*
J1420-0545 designation in Simbad: NVSS J142023-054532
J1420-0545 also known as: NVSS J142023-054532
Reason for selection of J1420-0545: Explicit superlative
Notes on J1420-0545: Redshift: 0.3067
Works where J1420-0545 referred to as superlative: Machalski et al. (2008); Kuźmicz et al. (2018)
References for data on J1420-0545: Machalski et al. (2008)

2.10.4 Water megamasers

$\mathbf{EIRP}_{\mathrm{H_2O}}$ **(brightest):** 23,000 $L_{\odot}$ – J0804+3607 [654]

Description: Highest apparent (isotropic) luminosity in 22 GHz water line
Evaluation as true superlative: ✓ – Much brighter masers would be easier to detect.

J0804+3607 *is sidereal source*
J0804+3607 designation in Simbad: FIRST J080431.0+360718
J0804+3607 also known as: FIRST J080431.0+360718
Reason for selection of J0804+3607: Explicit superlative

Notes on J0804+3607: Redshift: 0.660 (Barvainis & Antonucci 2005); brightest water megamaser listed in Zhang et al. (2012c)
Works where J0804+3607 referred to as superlative: Barvainis & Antonucci (2005)
References for data on J0804+3607: Barvainis & Antonucci (2005)

2.11 Galaxy associations

2.11.1 Galaxy groups

ρ (densest): ~ 2 M$_\odot$ pc^{-3} – HCG 54 [655]; ~ 0.3 M$_\odot$ pc^{-3} – Seyfert's Sextet [656]

Description: Highest total mass density
Evaluation as true superlative: ✓? + R? – HCG 54 is not clearly a compact group, but if it is, it is clearly an extreme example. (Note the matter density in the Solar neighborhood is 0.05 M$_\odot$ pc^{-3} for stars (Chabrier 2001) and 0.008 M$_\odot$ pc^{-3} for dark matter (Bovy & Tremaine 2012).)
Caveats about superlative category: The densities are from Hickson et al. (1992), which assumes $H_0 = 100$ km s^{-1} Mpc^{-1}.

HCG 54 *is sidereal source*
Reason for selection of HCG 54: Densest listed in Hickson et al. (1992)
Caveats about selection of HCG 54: Verdes-Montenegro et al. (2002) argues that HCG 54 is actually the remnant of a galaxy merger
Notes on HCG 54: Median galaxy separation: $2.3(h/0.7)^{-1}$ kpc (lowest by far in Hickson et al. 1992); chain of four dwarf galaxies (Hickson et al. 1989; Hickson 1993)
References for data on HCG 54: Hickson et al. (1992)

Seyfert's Sextet *is sidereal source*
Seyfert's Sextet designation in Simbad: Seyfert Sextet
Seyfert's Sextet also known as: HCG 79
Reason for selection of Seyfert's Sextet: Explicit superlative
Notes on Seyfert's Sextet: Median galaxy separation: $9.7(h/0.7)^{-1}$ kpc (Hickson et al. 1992); diameter: 23 kpc (Tamburri et al. 2012)
Works where Seyfert's Sextet referred to as superlative: Hickson (1997); Durbala et al. (2008)
References for data on Seyfert's Sextet: Hickson et al. (1992)

2.11.2 Galaxy clusters

M (largest): $(2.9^{+0.36}_{-0.32}$–$3.4^{+0.4}_{-0.4}) \times 10^{15}$ M$_\odot$ – Abell 370 [657]

Description: Highest virial mass, including dark matter
Evaluation as true superlative: ✓ – More massive clusters would be brighter and easier to detect; limited by cosmic structure growth history.

Abell 370 *is sidereal source*
Reason for selection of Abell 370: Explicit superlative
Notes on Abell 370: Virial mass: $2.93^{+0.36}_{-0.32}(h/0.7) \times 10^{15}$ M$_\odot$ (Broadhurst et al. 2008), $(3.4 \pm 0.4)(h/0.7) \times 10^{15}$ M$_\odot$ (Umetsu et al. 2011)
Works where Abell 370 referred to as superlative: Broadhurst et al. (2008); Umetsu et al. (2011)
References for data on Abell 370: Broadhurst et al. (2008); Umetsu et al. (2011)

M (largest, $z > 0.5$): $\sim (2.8 \pm 0.4) \times 10^{15}$ M$_\odot$ – MACS J0717.5+34 [658]

Description: Redshift: 0.55; highest mass galaxy cluster observed at redshift greater than 0.5
Evaluation as true superlative: ✓ – More massive clusters would be brighter and easier to detect; limited by cosmic structure growth history.

MACS J0717.5+34 *is sidereal source*
MACS J0717.5+34 designation in Simbad: ClG J0717+3745
Reason for selection of MACS J0717.5+34: Explicit superlative
Works where MACS J0717.5+34 referred to as superlative: Medezinski et al. (2013)

References for data on MACS J0717.5+34: Medezinski et al. (2013)
Other works on MACS J0717.5+34: Pandey-Pommier et al. (2013); Bonafede et al. (2009); van Weeren et al. (2009, 2019)

$\mathcal{R}$ **(richest):** 5 – Abell 665 [659]

Description: Highest richness class in Abell catalog, based on the number of galaxies only 2 magnitudes greater than the third brightest galaxy in the cluster
Evaluation as true superlative: ✓ – Limit by definition of Abell catalog richness.

Abell 665 *is sidereal source*
Reason for selection of Abell 665: Implicit superlative: only Abell cluster with richness class 5
Works where Abell 665 referred to as superlative: Abell et al. (1989)
References for data on Abell 665: Abell et al. (1989)

$\mathbf{L}_X$ **(brightest):** $2.14^{+0.03}_{-0.05} \times 10^{12}$ $L_\odot$ – Phoenix Cluster [660]

Description: Highest integrated 2-10 keV luminosity
Evaluation as true superlative: ✓ – Brighter clusters would be easier to detect.

Phoenix Cluster *is sidereal source*
Phoenix Cluster designation in Simbad: SPT-CL J2344-4243
Phoenix Cluster also known as: SPT-CL J2344-4243
Reason for selection of Phoenix Cluster: Explicit superlative
Notes on Phoenix Cluster: Redshift: 0.596
Works where Phoenix Cluster referred to as superlative: McDonald et al. (2012)
References for data on Phoenix Cluster: McDonald et al. (2012)
Relationships between Phoenix Cluster and other Exotica Catalog objects: Gravitationally lenses: SPT-CLJ2344-4243 Arc [641]

$\mathbf{T}_{\mathrm{ICM}}$ **(hottest):** 14.2 ± 0.3 keV – Bullet Cluster [509]

Description: Highest temperature intracluster medium
Evaluation as true superlative: ✓ – Limited by available energy (peculiar velocities) in colliding galaxy clusters.

Bullet Cluster *is sidereal source*
Bullet Cluster also known as: 1E 0657-56
Reason for selection of Bullet Cluster: Explicit possible superlative
Notes on Bullet Cluster: Redshift: 0.296; original temperature measurement by Tucker et al. (1998): 17.4 ± 2.5 keV
Works where Bullet Cluster referred to as superlative: Tucker et al. (1998)
References for data on Bullet Cluster: Wik et al. (2014)
Other works on Bullet Cluster: Markevitch et al. (2002); Clowe et al. (2006)
Relationships between Bullet Cluster and other Exotica Catalog objects: Gravitationally lenses: J 06587-5558 [692]

z **(furthest, X-ray):** 2.506 – CL J1001+0220 [661]

Description: Highest redshift galaxy cluster from which X-rays are detected, indicating the formation of the intracluster medium
Evaluation as true superlative: ✓? – Expected to be limited by time since Big Bang needed for structure to form.

CL J1001+0220 *is sidereal source*
CL J1001+0220 designation in Simbad: ClG J1001+0220
Reason for selection of CL J1001+0220: Explicit superlative
Works where CL J1001+0220 referred to as superlative: Wang et al. (2016)
References for data on CL J1001+0220: Wang et al. (2016)

2.11.3 Radio halos

$\mathbf{L}_{1.4\ \mathbf{GHz}}$ **(brightest):** 0.26–0.4 $L_\odot$ Hz^{-1} – MACS J0717.5+34 [658]

Description: Highest luminosity per unit frequency at 1.4 GHz from radio continuum emission
Evaluation as true superlative: ✓ – Brighter radio halos would be easier to detect.

MACS J0717.5+34 *is sidereal source*
MACS J0717.5+34 designation in Simbad: ClG J0717+3745
Reason for selection of MACS J0717.5+34: Explicit superlative
Notes on MACS J0717.5+34: $L_{1.4\ \mathrm{GHz}}$: 0.42 $L_\odot$ Hz^{-1} (Bonafede et al. 2009), 0.258 $L_\odot$ Hz^{-1} (Pandey-Pommier et al. 2013)
Works where MACS J0717.5+34 referred to as superlative: Bonafede et al. (2009); Pandey-Pommier et al. (2013); van Weeren et al. (2019)
References for data on MACS J0717.5+34: Bonafede et al. (2009); Pandey-Pommier et al. (2013)
Other works on MACS J0717.5+34: Pandey-Pommier et al. (2013); Bonafede et al. (2009); van Weeren et al. (2009, 2019); Medezinski et al. (2013)

2.11.4 Radio relics

$L_{1.4\ \mathrm{GHz}}$ (brightest): 0.13 $L_\odot$ Hz^{-1} – MACS J0717.5+34 [658]

Description: Highest luminosity per unit frequency at 1.4 GHz from radio continuum emission
Evaluation as true superlative: ✓ – Brighter radio relics would be easier to detect.

MACS J0717.5+34 *is sidereal source*
MACS J0717.5+34 designation in Simbad: ClG J0717+3745
Reason for selection of MACS J0717.5+34: Explicit superlative
Caveats about selection of MACS J0717.5+34: May not actually be a relic but some other filamentary structure (Bonafede et al. 2009), is a "chair-shaped" filament in the cluster's radio halo according to Pandey-Pommier et al. (2013)
Works where MACS J0717.5+34 referred to as superlative: van Weeren et al. (2009, 2019)
References for data on MACS J0717.5+34: van Weeren et al. (2009)
Other works on MACS J0717.5+34: Pandey-Pommier et al. (2013); Bonafede et al. (2009); van Weeren et al. (2019); Medezinski et al. (2013)

2.11.5 Protoclusters

z (furthest): 8.38 – A2744z8OD [662]

Description: Highest redshift
Status as true superlative unknown

A2744z8OD *is sidereal source*
A2744z8OD designation in Simbad: [IKO2015] HFF1C-Y5
Reason for selection of A2744z8OD: Among highest values we found in literature, highest listed in Table 3 of Harikane et al. 2019; high overdensity
Notes on A2744z8OD: Redshift is for galaxy Y5 (=A2744_YD4) in overdensity; unusually dense protocluster according to Ishigaki et al. (2016); overdensity: $\sim 132^{+66}_{-51}$ (Ishigaki et al. 2016)
References for data on A2744z8OD: Laporte et al. (2017)

2.12 Large scale structure

2.12.1 Galaxy superclusters

M (largest): $\sim (2\text{–}7) \times 10^{16}$ $M_\odot$ – Shapley Supercluster [663]

Description: Highest total mass
Evaluation as true superlative: ✓ – Larger superclusters in the local Universe would be evident in galaxy maps (as the "Great Walls" are). Supercluster size also limited by cosmic structure growth history.

Shapley Supercluster *is sidereal source*
Reason for selection of Shapley Supercluster: Explicit superlative within "nearby" Universe

Notes on Shapley Supercluster: The total mass depends on how supercluster is defined: Chon et al. (2015) finds a mass $1.9(h/0.7) \times 10^{16}$ $M_{\odot}$ within a collapse radius $17.7(h/0.7)$ Mpc, within which galaxies will eventually fall into the core (a "superstes-cluster"); Muñoz & Loeb (2008) finds a total mass within 50 Mpc of $(4.4 \pm 0.4) \times 10^{16}$ $M_{\odot}$; Proust et al. (2006) estimates a total mass of $7(h/0.7) \times 10^{16}$ $M_{\odot}$ in the entire structure

Works where Shapley Supercluster referred to as superlative: Bardelli et al. (1994); Kocevski & Ebeling (2006); Merluzzi et al. (2015)

References for data on Shapley Supercluster: Chon et al. (2015); Proust et al. (2006)

3. Anomalies (Non-SETI)

We group Anomalies into five numerical classes, with an additional "Class 0" to indicate objects that are not Anomalous even if they are extreme or have ambiguous natures. From the main *Exotica Catalog* paper:

- Class 0 objects are those that are not anomalous from an astrophysical point of view, although they can be exotic in terms of SETI. We define Class 0 anomalies as a likely member of a known, explained population even if classification is ambiguous, with no evidence for unknown phenomena at work. Almost all of the Prototypes and Superlatives fall in Class 0. An object can still have ambiguous classification without actually being mysterious; Pluto in the early 2000s was Class 0. Alternatively, an object that is unidentified because it has multiple good explanations remains Class 0: IRAS 19312+1950 may be either a young star or an AGB, but seems readily explainable (Nakashima et al. 2011; Cordiner et al. 2016).

- Class I anomalies are likely members of a known, explained population, with normal intrinsic properties, but located in an anomalous environment or context. In other words, the object itself is not mysterious, only where it is. This also includes objects with inexplicable kinematics. Hot Jupiters were Class I anomalies until it was understood that gas giants could migrate (Mayor & Queloz 1995; Guillot et al. 1996).

- Class II anomalies are likely members of a known, explained class, but whose properties quantitatively fall far outside the usual distribution. Class II anomalies are qualitatively similar to other objects of the same type. Millisecond pulsars, for a short time after discovery, were Class II because of their extreme spin (Backer et al. 1982). Candidate megastructures identified by infrared emission in excess of the expected value (as identified by the far–infrared radio correlation of galaxies, for example; Garrett 2015; Zackrisson et al. 2015) or abnormally faint optical emission (Annis 1999; Zackrisson et al. 2018) are examples in a SETI context.

- Class III anomalies are likely members of a known, explained class, but displaying a qualitatively new and unexplained phenomenon. These phenomena generally are not even observed around most (or any other) members of the class. Saturn's rings are a classical example, as their nature as debris belts took centuries to understand despite Saturn clearly being a planet (Dick 2013). Candidate SETI signals found in targeted surveys of nearby stars through the traditional methods of ultranarrowband radio emission or nanosecond optical pulses would be Class III anomalies.

- Class IV anomalies are members of an unexplained or unknown phenomenon class. They may be identified only in one waveband, without counterparts in any others. Current explanations generally have plausibility issues. Many of the famous discoveries of the past century were originally Class IV anomalies: among them, Galactic synchrotron emission (Jansky 1933), quasars (Schmidt 1963), pulsars (Hewish et al. 1968), gamma-ray bursts (Klebesadel et al. 1973; Nemiroff 1994), and now fast radio bursts (Lorimer et al. 2007; Platts et al. 2019). They are, however, relatively rare. Candidate SETI signals found in wide-field surveys are frequently Class IV, including the Wow! signal (Dixon 1985; Gray & Ellingsen 2002).

- Class V anomalies are objects or phenomena that appear to defy known laws of physics, whether the object itself is identifiable or not. These are extremely rare. In very special cases they may herald an upheaval in our understanding, as the Galilean satellites and solar neutrino problem did, but usually they are simply in error (e.g, the notorious case of candidate superluminal neutrinos in an early version of Adam et al. 2012, which was a non-localized Class V anomaly).

Anomalies that are partially explained or have plausible theories for their nature can have a class that starts with "0/" to indicate partial membership in Class 0. Some Anomalies may have multiple classes listed. In these, the class depends on the interpretation of the Anomaly; the primary class is listed first (after "0/" if present).

3.1 Class I

Pulsar planets: PSR B1257+12 [094]

Notes on anomaly: Terrestrial pulsar planets appear to generally be rare (Kerr et al. 2015; Martin et al. 2016). Several giant pulsar planets are known and may form more conventionally. Single giant planet-mass companions in close orbits are

generally explained as the remnants of companion stars.
References for anomaly: Wolszczan & Frail (1992); Phinney & Hansen (1993); Podsiadlowski (1993); Hansen et al. (2009); Martin et al. (2016)

PSR B1257+12 *is sidereal source*
Elaboration of anomaly in PSR B1257+12: System of three terrestrial-size planets in orbit around millisecond pulsar host. Original planets around progenitor star are not expected to survive its supernova. As a millisecond pulsar, PSR B1257+12 is expected to have gone through an X-ray binary phase that should have sublimated rocky material.
Notable theories for PSR B1257+12: Planets forming out of supernova fallback disk (Lin et al. 1991; Hansen et al. 2009), during XRB phase with accretion disk shielding planets from radiation (Tavani & Brookshaw 1992), from material of disrupted companion star at end of XRB phase (Stevens et al. 1992b) or stellar merger (Margalit & Metzger 2017b); pulsar suggested to be born as millisecond pulsar (Miller & Hamilton 2001)
Anomaly class for PSR B1257+12: I (III) – Terrestrial planets common, but unclear how they could have formed or survived the XRB phase (and possibly preceding supernova), making their location unusual (I), theories exist but generally considered mysterious still; planets could be regarded as unusual attribute of host pulsar (III)
References for this anomaly in PSR B1257+12: Wolszczan & Frail (1992); Konacki & Wolszczan (2003)
Other references for PSR B1257+12: Konacki & Wolszczan (2003); Wolszczan & Frail (1992); Schneider et al. (2011)

Paradoxical extremely-low mass white dwarfs: KIC 8145411 [332]; HE 0430-2457 [664]

Description of anomaly: Extremely-low mass dwarf found in long-period orbit around primary star, too distant for mass transfer (the usual mechanism for ELM white dwarf formation) to have occurred
Notable theories for anomaly: Mass transfer from former close companion of WD, followed by high mass loss during merger
Anomaly class: 0/I – ELM WDs generally expected to be found close to primary so mass transfer can occur, some theories exist with stellar merger a leading candidate (0) although Masuda et al. (2019) considers circular orbit of WD unexplained.

KIC 8145411 *is sidereal source*
Notable theories for KIC 8145411: Unseen tertiary star perturbed orbit so that red giant progenitor of WD was truncated and WD orbit somehow circularized (considered unlikely by Masuda et al. 2019)
Notes on anomalous KIC 8145411: P: 455.83 ± 0.01 day; e: 0.14 ± 0.02; M_{WD}: 0.20 ± 0.01 $\mathrm{M}_{\odot}$
References for this anomaly in KIC 8145411: Masuda et al. (2019)
Other references for KIC 8145411: Masuda et al. (2019)

HE 0430-2457 *is sidereal source*
Notable theories for HE 0430-2457: Vos et al. (2018) favors stellar merger theory.
Notes on anomalous HE 0430-2457: P: 771 ± 3 day; small eccentricity; M_{WD}: 0.23 ± 0.05 $\mathrm{M}_{\odot}$
References for this anomaly in HE 0430-2457: Vos et al. (2018)

Peripheral millisecond pulsar binaries: PSR J1911-5958A [665]; PSR J1740-5340 [666]

Description of anomaly: Millisecond pulsar-secondary binaries found at the edge of a globular cluster, when dynamical friction should push it towards center
Notable theories for anomaly: Unusual location possibly result of close stellar encounter in past
Anomaly class: I – Found in wrong place in globular cluster; dynamical explanation in terms of close encounters, but these examples have other anomalous features (see below) suggesting something more is at work.

PSR J1911-5958A *is sidereal source*
Elaboration of anomaly in PSR J1911-5958A: Located 74 core radii from center of NGC 6752
Notable theories for PSR J1911-5958A: Other millisecond pulsars in NGC 6752 have unusual location (PSR J1911-6000C), or are close to core but have unusually high accelerations (PSR J1910-5959B, PSR J1910-5959D, PSR J1910-5959E), suggesting interactions with dark mass (possibly binary black hole) in center of cluster (D'Amico et al. 2002; Ferraro et al. 2003b)
Notes on anomalous PSR J1911-5958A: Secondary is white dwarf; also displays unusual light curve (see below)
References for this anomaly in PSR J1911-5958A: Colpi et al. (2003); Ferraro et al. (2003a)
Other references for PSR J1911-5958A: Cocozza et al. (2006)
Relationships between PSR J1911-5958A and other Exotica Catalog objects: Within the sky region occupied by: NGC 6752 [340]

PSR J1740-5340 *is sidereal source*
Elaboration of anomaly in PSR J1740-5340: Located 11 core radii from center of NGC 6397
Notes on anomalous PSR J1740-5340: Secondary is unusual red straggler (see below)
References for this anomaly in PSR J1740-5340: Orosz & van Kerkwijk (2003)
Other references for PSR J1740-5340: Mucciarelli et al. (2013); D'Amico et al. (2001); Orosz & van Kerkwijk (2003)

Nuclear cluster stars: S0-2 [667]; IRS 16C [668]

Description of anomaly: Young, high-mass stars found very close to Galactic Center, where tides are expected to inhibit stellar formation
Notable theories for anomaly: Formation *in situ* despite tides; accretion of stars onto Central Cluster from a tidally disrupted cluster
References for anomaly: Gerhard (2001); Ghez et al. (2003); Levin & Beloborodov (2003); Lu et al. (2009)
Anomaly class: I – Location near Sgr A* difficult to explain; several theories exist but none seems satisfying as of yet

S0-2 *is sidereal source*
S0-2 also known as: S2
Elaboration of anomaly in S0-2: S stars are B dwarfs found very close to Sgr A* ($\lesssim 1''$).
Notable theories for S0-2: Additional theories for apparent stellar "rejuvenation" for S stars due to high rate of stellar interactions.
Notes on anomalous S0-2: S0-2 is one of the best studied examples, among the closest to Sgr A* and thus is chosen for the S stars; age: $6.6^{+3.4}_{-4.7}$ Myr
References for this anomaly in S0-2: Ghez et al. (2003); Gillessen et al. (2009); Habibi et al. (2017)
Other references for S0-2's host: Gravity Collaboration et al. (2019b)
Relationships between S0-2 and other Exotica Catalog objects: Within the sky region occupied by: Central Cluster [343]; Orbital primary: Sgr A* [471]; Adjacent on sky to (sharing parent object with): G2 [669], IRS 16E [604], IRS 16C [668], S4711 [574]

IRS 16C *is sidereal source*
Elaboration of anomaly in IRS 16C: Wolf-Rayet/O supergiant stellar population found within central parsec among two counterrotating disks
Notes on anomalous IRS 16C: IMF of the WR/O disks appears to be top-heavy (Bartko et al. 2010; Lu et al. 2013); age: 6 ± 2 Myr
References for this anomaly in IRS 16C: Gravity Collaboration et al. (2019b)
Relationships between IRS 16C and other Exotica Catalog objects: Within the sky region occupied by: Central Cluster [343]; Orbital primary: Sgr A* [471]; Adjacent on sky to (sharing parent object with): G2 [669], IRS 16E [604], S0-2 [667], S4711 [574]

Nuclear subcluster: IRS 16E [604]

IRS 16E *is sidereal source*
Elaboration of anomaly in IRS 16E: Apparent extremely dense star subcluster only 0.1 pc from Galactic Center (projected), possibly within tidal disruption limit
Notable theories for IRS 16E: Possibly chance projection of unbound stars, or further from Galactic Center
Anomaly class for IRS 16E: I – Survival of subcluster difficult to explain in its location, if real; also contains unexplained nuclear cluster stars (see above)
Notes on anomalous IRS 16E: Stars include Wolf-Rayet stars and O supergiant; if actually a cluster of projected size ($0.3''$ radius), would be among densest known (see Superlatives)
References for this anomaly in IRS 16E: Paumard et al. (2006); Fritz et al. (2010); Wang et al. (2020); Zhu et al. (2020)
Other references for IRS 16E: Paumard et al. (2006); Fritz et al. (2010)
Other references for IRS 16E's host: Gravity Collaboration et al. (2019b)
Relationships between IRS 16E and other Exotica Catalog objects: Within the sky region occupied by: Central Cluster [343]; Orbital primary: Sgr A* [471]; Adjacent on sky to (sharing parent object with): G2 [669], IRS 16C [668], S0-2 [667], S4711 [574]

Nuclear cluster cloud: G2 [669]

G2 *is sidereal source*

Elaboration of anomaly in G2: Odd compact cloud on close orbit around Sgr A*
Notable theories for G2: Self-gravitating cloud, or cloud surrounding star
Anomaly class for G2: I/IV – Unclear how cloud could survive in its present orbit around Sgr A* (I); object nature and formation also unclear (IV)
Notes on anomalous G2: Famously had a close passage to Sgr A* in 2013
References for this anomaly in G2: Gillessen et al. (2012); Phifer et al. (2013); Plewa et al. (2017)
Other references for G2's host: Gravity Collaboration et al. (2019b)
Relationships between G2 and other Exotica Catalog objects: Within the sky region occupied by: Central Cluster [343]; Orbital primary: Sgr A* [471]; Adjacent on sky to (sharing parent object with): IRS 16E [604], IRS 16C [668], S0-2 [667], S4711 [574]

Displaced supernovae: ASASSN -14jb [670]; SN 2009ip [671]

Description of anomaly: Core collapse supernova, well beyond star-forming regions of galaxy

ASASSN -14jb *is sidereal source*
Elaboration of anomaly in ASASSN -14jb: Type II supernova occuring 2 kpc above edge-on host galaxy's plane
Notable theories for ASASSN -14jb: Progenitor star formed in-situ off galactic plane, or is runaway star ejected from plane by companion star
Anomaly class for ASASSN -14jb: 0/I – Core collapse supernova result from massive stars with short lifetimes, found almost entirely within galactic disks (I); Meza et al. (2019) propose two explanations both consistent with modeled supernova progenitor properties, suggesting essentially viable explanations (0)
Notes on anomalous ASASSN -14jb: Host galaxy: ESO 467-G051
References for this anomaly in ASASSN -14jb: Meza et al. (2019)

SN 2009ip *is sidereal source*
Elaboration of anomaly in SN 2009ip: Core collapse supernova on distant outskirts of host galaxy, $\gtrsim$ 1.5 kpc from any bright star-formation regions; progenitor apparently was LBV of $\sim$ 50–80 $M_\odot$
Notable theories for SN 2009ip: Progenitor may have formed in very small star-formation region, or be the result of binary mass transfer
Anomaly class for SN 2009ip: I – Luminous blue variables are massive and should only be found in high-mass star-formation regions, making its location very hard to explain unless mass transfer is involved
Notes on anomalous SN 2009ip: Host galaxy: NGC 7259; progenitor appears to have undergone LBV eruptions in 2009–2010 before finally going supernova in 2012 (Mauerhan et al. 2013; Graham et al. 2017), although core collapse has been disputed (Fraser et al. 2013, 2015); event involves interaction with circumstellar material
References for this anomaly in SN 2009ip: Fraser et al. (2013); Smith et al. (2016)
Other references for SN 2009ip: Mauerhan et al. (2013); Graham et al. (2017); Fraser et al. (2015)

Hypervelocity globular cluster: HVGC-1 [672]

HVGC-1 *is sidereal source*
Elaboration of anomaly in HVGC-1: Intergalactic globular cluster near Virgo Cluster with peculiar velocity $\sim$ 1,000 km s^{-1}
Notable theories for HVGC-1: Ejection by interaction with Virgo Cluster subhalo or M87 supermassive black hole, or during halo merger
Anomaly class for HVGC-1: 0/I – Peculiar velocity far in excess of expected for velocity distribution (I); Caldwell et al. (2014) and Samsing (2015) suggest some dynamical origins (0), but cluster is poorly studied
References for this anomaly in HVGC-1: Caldwell et al. (2014); Samsing (2015)
Relationships between HVGC-1 and other Exotica Catalog objects: Within the sky region occupied by: Virgo Cluster [506]

Peculiar offset active galactic nuclei: 3C 186 [673]; SDSS J113323.97+550415.9 [674]

Description of anomaly: Active galactic nuclei found offset both in position and velocity from center of host
Notable theories for anomaly: Supermassive black hole kicked from recoil after merger with companion black hole
References for anomaly: Merritt et al. (2004)

3C 186 *is sidereal source*
Anomaly class for 3C 186: 0/I – Location and velocity atypical of AGN (I), but plausible explanation exists in form of recoiled SMBH (0)

Notes on anomalous 3C 186: Projected distance from host galaxy center: 11 kpc; broad absorption lines offset by $\sim -2{,}100$ km s^{-1} from galaxy, narrow-line region has several components but "peak" at $-1{,}800$ km s^{-1}
References for this anomaly in 3C 186: Chiaberge et al. (2017, 2018)

SDSS J113323.97+550415.9 *is sidereal source*
SDSS J113323.97+550415.9 also known as: Gaia 19bwn
Elaboration of anomaly in SDSS J113323.97+550415.9: Unusual transient with variability consistent with AGN, but displaced by 6″ from Mkn 177
Notable theories for SDSS J113323.97+550415.9: Koss et al. (2014) proposed it could be an erupting luminous blue variable
Anomaly class for SDSS J113323.97+550415.9: 0/I/IV – Location atypical for AGN (I), possible explanation in form of recoiled SMBH (0), but not clear that it is an AGN instead of an unknown object of another type (IV)
Notes on anomalous SDSS J113323.97+550415.9: Velocity offset is low, suggesting it may not be a recoiling AGN; radio-quiet
References for this anomaly in SDSS J113323.97+550415.9: Koss et al. (2014); Perez-Torres et al. (2015); Stanek et al. (2019); Pursimo et al. (2019)

3.2 Class II

Extreme comet outburst: 17P/Holmes [675]

17P/Holmes *is Solar System source*
Elaboration of anomaly in 17P/Holmes: Unexplained brightening of comet by a factor $\sim 10^6$ in 2007, with previous large outburst in 1892
Notable theories for 17P/Holmes: Explosion of material off comet: possibly subsurface heating of volatile gas cavity, or rapid conversion of suface amorphous water ice to crystalline water ice; survival after multiple explanations hard to explain
Anomaly class for 17P/Holmes: 0/II – Although comets are well-known to have outbursts, the magnitude of the 2007 outburst of 17P/Holmes was exceptional (II); the fact that theories exist and it simply seems to be the tail of a distribution lowers its anomalousness (0)
References for this anomaly in 17P/Holmes: Montalto et al. (2008); Reach et al. (2010); Hsieh et al. (2010)
Relationships between 17P/Holmes and other Exotica Catalog objects: Orbital primary: Sun [150]

Underheated ice giant: Uranus [676]

Uranus *is Solar System source*
Elaboration of anomaly in Uranus: Solar System ice giant with no significant internal heat flux detected, despite expectations and existence of large heat flux in similar Neptune
Notable theories for Uranus: Heat transport from interior suppressed, possibly by compositional gradient inhibiting convection; alternatively, original heat already lost
Anomaly class for Uranus: 0/II – Internal luminosity is a quantity starkly different from other Solar System giant planets (II), but plausible mechanism exists for suppression of heat transport (0).
Notes on anomalous Uranus: The axial tilt of Uranus is famously large compared to Solar System giant planets.
References for this anomaly in Uranus: Pearl et al. (1990); Podolak et al. (1991); Fortney et al. (2011); Vazan & Helled (2020)
Relationships between Uranus and other Exotica Catalog objects: Hosts (is primary of): Miranda [550]; Orbital primary: Sun [150]

Super-puffs: HIP 41378 f [677]

Description of anomaly: Super-Earth or small giant planets with extremely low mean density ($\lesssim 0.1$ g cm^{-3}), lower even than typical "inflated" gas giants, as determined from transits and radial velocity methods; typically short period, but can exist in temperate regions and thus not necessarily result of heating or tidal effects.
Notable theories for anomaly: Large apparent radius due to transit of large rings (Piro & Vissapragada 2020) or thick dusty envelopes (Libby-Roberts et al. 2020) or winds surrounding planet.
References for anomaly: Lee & Chiang (2016); Wang & Dai (2019); Libby-Roberts et al. (2020); Piro & Vissapragada (2020)

HIP 41378 f *is sidereal source*
Anomaly class for HIP 41378 f: II – Defined by extremely small density (large radius), explanation unknown

Notes on anomalous HIP 41378 f: Density: 0.09 g cm^{-3}; surface temperature: $\sim$ 300 K
References for this anomaly in HIP 41378 f: Santerne et al. (2019); Piro & Vissapragada (2020)

Further examples of anomaly: Kepler 79 d (Jontof-Hutter et al. 2014), Kepler 51 bcd
Relationship to SETI: Arnold (2005) proposes anomalous transits by planet-size megastructures as technosignature

Anomalous abundance star: λ Boo [207]; HD 65949 [678]; Przybylski's Star [679]; HD 106038 [680]; HD 135485 [681]; LS IV-14 116 [682]; 2MASS J13535604+4437076 [683]

Description of anomaly: Stars with unusual abundances of certain elements that are difficult to explain through normal stellar evolution.

λ **Boo** *is sidereal source*
Elaboration of anomaly in λ Boo: Prototype of class of stars with as-yet unexplained depletions in iron-peak elements, consistent with ISM material but with accretion of dust somehow suppressed
Notes for type of anomaly in λ Boo: Many are unresolved binaries
Notable theories for λ Boo: Source of accreted matter unknown, but has been proposed to be ISM, circumstellar gas, and hot Jupiters; Murphy & Paunzen (2017) proposes radiation pressure blows away dust in accreted matter, but there may be multiple ways for their evolution
Anomaly class for λ Boo: 0/II – Anomaly defined by quantitatively unusual abundances (II); where the stars are getting their accreted matter from is not entirely clear, but several theories exist (0)
References for type of anomaly in λ Boo: Venn & Lambert (1990); Gerbaldi et al. (2003); Murphy & Paunzen (2017)
Other references for λ Boo: Ciardi et al. (2007)
λ Boo in I17

HD 65949 *is sidereal source*
Elaboration of anomaly in HD 65949: Star that is extremely rich in elements $Z = 75$–80 (rhenium through mercury); has an odd-Z anomaly (odd-Z elements richer than even-Z elements of similar Z), unusually at zirconium, niobium, and molybdenum ($Z = 40$–42); extreme abundance fall-off between xenon and barium
Notable theories for HD 65949: "Exotic" mass accretion from supernova followed by differentiation in atmosphere (Cowley et al. 2010)
Anomaly class for HD 65949: II – The quantities of elements are highly unusual (II), although Cowley et al. (2010) proposes a model
Notes on anomalous HD 65949: Located in young cluster NGC 2516, which is unusually rich in chemically peculiar stars; part of a binary or triple system
References for this anomaly in HD 65949: Cowley et al. (2010)

Przybylski's Star *is sidereal source*
Przybylski's Star also known as: HD 101065
Elaboration of anomaly in Przybylski's Star: Star with unusually large amounts of rare-earth elements and very short-lived elements, including promethium (half life: 18 yr)
Anomaly class for Przybylski's Star: II – Quantities of heavy elements unexplained as of yet, radioactive elements may indicate very unusual process at work (class III)
Notes on anomalous Przybylski's Star: Discussed as a possible technosignature in https://sites.psu.edu/astrowright/2017/03/15/przybylskis-star-i-whats-that/ and subsequent articles in the series, and mentioned in the literature in (Wright 2018a).
References for this anomaly in Przybylski's Star: Przybylski (1961); Cowley et al. (2004); Bidelman (2005); Gopka et al. (2008)

HD 106038 *is sidereal source*
Elaboration of anomaly in HD 106038: Metal-poor star ($[Fe/H] = -1.3$) with unusually high beryllium abundance; some other elements are overabundant; cannot be explained through simple cosmic ray spallation
Notable theories for HD 106038: Abundance pattern possibly result of hypernova, or combination of r- and s-process sources
Anomaly class for HD 106038: 0/II – Abundance of beryllium quantitatively stands out (II), but explanations exist (0)
References for this anomaly in HD 106038: Smiljanic et al. (2008); Hansen et al. (2017)

HD 135485 *is sidereal source*
Elaboration of anomaly in HD 135485: Metal-rich star ($\sim$ 3 $Z_\odot$) but with low nickel abundance and extremely high manganese abundance

Anomaly class for HD 135485: II – Anomalousness defined by unusual quantities of manganese and nickel.
References for this anomaly in HD 135485: Trundle et al. (2001)

LS IV-14 116 *is sidereal source*
Elaboration of anomaly in LS IV-14 116: Hot subdwarf (sdB) overabundant in germanium, yttrium, strontium, and zirconium (10^3–10^4 solar)
Notable theories for LS IV-14 116: Possibly due to radiative levitation of ions of overabundant elements
Anomaly class for LS IV-14 116: 0/II – Abundances of these elements stand out quantitatively (II), but radiatively driven diffusion provides a mechanism and has produced similar patterns in some "normal" chemically peculiar stars (0).
Notes on anomalous LS IV-14 116: Star has anomalous variability (see below).
References for this anomaly in LS IV-14 116: Naslim et al. (2011)
Other references for LS IV-14 116: Randall et al. (2015); Naslim et al. (2011); Green et al. (2011)

2MASS J13535604+4437076 *is sidereal source*
Elaboration of anomaly in 2MASS J13535604+4437076: Phosphorus-rich (about 10–100) star with unexplained enrichment in other light metals and barium
Notable theories for 2MASS J13535604+4437076: Unusual (and as yet unexplained) enrichment of material that formed star, possibly with additional differentiation with rotation
Anomaly class for 2MASS J13535604+4437076: II – Quantitative abundance ratios unexplained (II); recent discovery without ready explanation
Notes on anomalous 2MASS J13535604+4437076: One of fifteen phosphorus-rich stars in Masseron et al. (2020); this one has a detailed spectrum
References for this anomaly in 2MASS J13535604+4437076: Masseron et al. (2020)

Relationship to SETI: Whitmire & Wright (1980) proposes anomalous abundance pattern due to dumping of nuclear waste material on stars with non-convective surface as technosignature

Anomalous red companion star: COM 6266B [684]

Description of anomaly: Abnormal red companion star to pulsar with radius too large to fit in Roche Lobe, as determined from color and brightness
Notes on anomaly: Companion is PSR J1701-3006B; eclipsing system; timing of pulsar in system indicates interaction (Lynch et al. 2012); host globular cluster: M62
Notable theories for anomaly: System closer than apparent host cluster, thought unlikely; unexplained nonthermal luminosity interfering with radius estimation (Cocozza et al. 2008)
References for anomaly: Cocozza et al. (2008); Lynch et al. (2012)
Anomaly class: II/V – Radius is abnormally big compared to expectations for such a close binary (II), and apparently defies compatibility with Roche lobe limit set by gravity (V)

COM 6266B *is sidereal source*

Subsubgiant: M67-S1063 [685]

Description of anomaly: Star redder than main sequence turnoff but fainter than subgiant branch in coeval star clusters
Notes on anomaly: Possibly related to red straggler stars, as defined by Geller et al. (2017).
Notable theories for anomaly: Several channels are thought to exist, including large sunspots on surface, tidal stripping by companion, and mass transfer in binary system
References for anomaly: Geller et al. (2017); Leiner et al. (2017)
Anomaly class: 0/II – Combination of temperature and luminosity significantly diverges from most other stars in cluster (II), but several mechanisms have been proposed to explain them (0).

M67-S1063 *is sidereal source*
Notes on anomalous M67-S1063: One of two examples identified in M67; in a spectroscopic binary, primary (1.3 $M_\odot$) is subsubgiant
References for this anomaly in M67-S1063: Belloni et al. (1998); Mathieu et al. (2003)
Relationships between M67-S1063 and other Exotica Catalog objects: Within the sky region occupied by: M67 [335]; Adjacent on sky to (sharing parent object with): M67-S1237 [231]

Further examples of anomaly: M67-S1113

Red straggler: PSR J1740-5340 [666]

Description of anomaly: Faint red giant stars that are redder than red giant branch stars of equal luminosity in coeval star clusters
Notes on anomaly: Possibly related to subsubgiants, as defined by Geller et al. (2017).
Notable theories for anomaly: Proposed to form by extreme mass loss of envelope
References for anomaly: Geller et al. (2017)
Anomaly class: 0/II – Combination of temperature and luminosity significantly diverges from most other stars in cluster (II), but envelope stripping is a viable mechanism for forming them (0).

PSR J1740-5340 *is sidereal source*
PSR J1740-5340 also known as: COM J1740-5340
Notes on anomalous PSR J1740-5340: Companion to PSR J1740-5340; modeled as 0.8 $M_\odot$ progenitor that transferred most mass to pulsar, leaving only 0.2 $M_\odot$ stripped star behind; system unusually far from host globular cluster's core (see above); wind from star eclipses pulsar
References for this anomaly in PSR J1740-5340: Orosz & van Kerkwijk (2003); Mucciarelli et al. (2013)
Other references for PSR J1740-5340: Mucciarelli et al. (2013); D'Amico et al. (2001); Orosz & van Kerkwijk (2003)

Bloatars: [SBD2011] 5 [686]

Description of anomaly: Luminous stellar objects observed in young stellar cluster NGC 3603 with effective temperatures $T \sim 2{,}000$ K
Notes on anomaly: Luminosity comparable to 0.2–1 $M_\odot$ pre-main sequence stars; essentially no follow up in literature
Notable theories for anomaly: Proposed to be stars that have consumed hot Jupiter recently
References for anomaly: Spezzi et al. (2011)
Anomaly class: II – Defined by abnormal combination of low temperature and moderate luminosity (II); explanation is proposed but bloatars have not been studied in detail.

[SBD2011] 5 *is sidereal source*
Notes on anomalous [SBD2011] 5: One of three L5 spectral class bloatars identified by Spezzi et al. (2011), is not contaminated and is relativelly bright
Other references for [SBD2011] 5's host: Fukui et al. (2014)
Relationships between [SBD2011] 5 and other Exotica Catalog objects: Within the sky region occupied by: NGC 3603 [359]; Adjacent on sky to (sharing parent object with): HD 97950 [606]

Kilosecond rotation magnetar: 1E 1613-5055 [687]

Notable theories for anomaly: Magnetar surrounded by fallback disk from supernova that brakes rotation, possibly through propeller mechanism (Ho & Andersson 2017), although difficult to achieve in models according to Xu & Li (2019)
Anomaly class: II – Rotation period stands out quantitatively; explanation exists in form of rotational braking by disk, but may require contrived paramaters

1E 1613-5055 *is sidereal source*
Elaboration of anomaly in 1E 1613-5055: Isolated X-ray pulsar with apparent 7 hour long rotation period, as inferred from X-ray variability
Notes on anomalous 1E 1613-5055: In supernova remnant RCW 103 with apparent age of 2,000 yr; displays magnetar-like outbursts
References for this anomaly in 1E 1613-5055: De Luca et al. (2006); Rea et al. (2016); Ho & Andersson (2017); Xu & Li (2019)

Paradoxical white dwarf binary: DWD HS 2220+2146 [688]

DWD HS 2220+2146 *is sidereal source*
Elaboration of anomaly in DWD HS 2220+2146: White dwarf-white dwarf binary, where more massive white dwarf appears to be younger, in contradiction to expectation of stellar evolution that more massive white dwarfs come from more massive stars

and form earlier than a companion; distance to companion is 500 AU, definitely precluding interaction with it

Notable theories for DWD HS 2220+2146: More massive white dwarf possibly result of merger of compact double white dwarf in former triple system

Anomaly class for DWD HS 2220+2146: 0/II – Anomaly is quantitative discrepancy between relative ages and masses of components (II); binary merger origin can explain features (0)

References for this anomaly in DWD HS 2220+2146: Andrews et al. (2016a)

Overmassive supermassive black holes: NGC 1277* [689]; Was 49b [690]

NGC 1277* *is sidereal source*

Elaboration of anomaly in NGC 1277:* Supermassive black hole claimed to have mass about 60% of stellar mass in massive early-type galaxy NGC 1277's (pseudo)-bulge, instead of the usual 0.1% fraction

Notable theories for NGC 1277:* Underestimation of spheroid mass and overestimation of black hole mass

Anomaly class for NGC 1277:* 0/II – Black holes apparently stands out quantitatively in mass (II), although it seems increasingly likely that measurement systematics dampen or remove the anomaly (0)

Notes on anomalous NGC 1277:* M_{SMBH}: 1.7×10^{10} $M_\odot$ van den Bosch et al. (2012), 5×10^9 $M_\odot$ (Emsellem 2013), $4.9 \pm 1.6 \times 10^9$ $M_\odot$ (Walsh et al. 2016), $(0.5–1.7) \times 10^{10}$ $M_\odot$ (Scharwächter et al. 2016), $\leq 1.2 \times 10^9$ $M_\odot$ (Graham et al. 2016); bulge/spheroid mass: 2.9×10^{10} $M_\odot$ (van den Bosch et al. 2012), 2.7×10^{11} $M_\odot$ (Graham et al. 2016); NGC 1277 is compact relic red nugget, which has been suggested to be related somehow to the (apparent) overmassive black hole

References for this anomaly in NGC 1277:* van den Bosch et al. (2012); Emsellem (2013); Walsh et al. (2016); Scharwächter et al. (2016); Graham et al. (2016)

Relationships between NGC 1277 and other Exotica Catalog objects:* Within the sky region occupied by: NGC 1277 [402], Perseus Cluster [508]

Was 49b *is sidereal source*

Elaboration of anomaly in Was 49b: Supermassive black hole in dwarf satellite companion to Was 49a that both unexpectedly outshines Was 49a AGN and has an unusually large mass for its satellite host; in a minor merger Was 49a, it is expected that the secondary's black hole will remain fainter

Anomaly class for Was 49b: II – Anomalous because of high luminosity ratio of Was 49b to primary's black hole, and high mass ratio of SMBH to host galaxy

Notes on anomalous Was 49b: Host shows no sign of tidal distortion, unlike ultracompact dwarfs; M_{SMBH}: $1.3^{+2.9}_{-0.9} \times 10^8$ $M_\odot$; M_{host}: $5.6^{+4.9}_{-2.9} \times 10^9$ $M_\odot$

References for this anomaly in Was 49b: Secrest et al. (2017)

Ultrapolarized radio sources: 2MASX J07390433+1804252 [691]; J 06587-5558 [692]

Description of anomaly: Extragalactic radio sources where synchrotron emission has unusually high linear polarization at some frequency

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2MASX J07390433+1804252 *is sidereal source*

Elaboration of anomaly in 2MASX J07390433+1804252: Radio galaxy with $60 \pm 17\%$ polarization at 1.4 GHz

Notable theories for 2MASX J07390433+1804252: Either synchrotron emission produced in an ISM with highly ordered magnetic fields, unexpected for elliptical galaxies, or host has rarefied ISM that prevents depolarization

Anomaly class for 2MASX J07390433+1804252: 0/II – The polarization is quantitatively extreme (II), but possible mechanisms for avoiding depolarization were proposed (0)

Notes on anomalous 2MASX J07390433+1804252: Shi et al. (2010) identifies several similar sources; this one has the highest polarization of those with both high-resolution radio and optical observations

References for this anomaly in 2MASX J07390433+1804252: Shi et al. (2010)

J 06587-5558 *is sidereal source*

Elaboration of anomaly in J 06587-5558: Resolved extragalactic radio source with 54% polarization at 8.87 GHz

Notable theories for J 06587-5558: Possibly lensed galaxy, consistent with location behind galaxy cluster; polarized radio emission may be from lensed image of part of a radio jet

Anomaly class for J 06587-5558: 0/II – The polarization is quantitatively extreme (II); plausible explanation in form of differential lensing (0)

Notes on anomalous J 06587-5558: Depolarized at 1.4 GHz; Johansson et al. (2012) identifies the source with the lensed star-forming galaxy SMM J065837.6-555705, also called the "Cosmic Seagull", the source of the distance and magnification used (Motta et al. 2018)

References for this anomaly in J 06587-5558: Liang et al. (2001); Shimwell et al. (2014)

Relationships between J 06587-5558 and other Exotica Catalog objects: Gravitationally lensed by: Bullet Cluster [509]

Hyperluminous supernova/tidal disruption event: ASASSN -15lh [693]

ASASSN -15lh *is sidereal source*

Elaboration of anomaly in ASASSN -15lh: Abnormally luminous optical transient; either the brightest superluminous supernova ever observed, challenging models, or an abnormally bright tidal disruption event by a supermassive black hole

Notable theories for ASASSN -15lh: Tidal disruption event by high-mass, high-spin supermassive black hole

Anomaly class for ASASSN -15lh: 0/II – Initially identified as superluminous supernova, but total released energy (2×10^{52} erg) defies explanation (II); tidal disruption event may explain energy (0), although Godoy-Rivera et al. (2017) argues emission more characteristic of supernova

Notes on anomalous ASASSN -15lh: Krühler et al. (2018) claims it is coincident with a supermassive black hole

References for this anomaly in ASASSN -15lh: Dong et al. (2016); Leloudas et al. (2016); Godoy-Rivera et al. (2017); Krühler et al. (2018)

Cosmic microwave background cold spot: CMB Cold Spot [694]

CMB Cold Spot *is sidereal source*

Elaboration of anomaly in CMB Cold Spot: Unusually deep temperature fluctuation with 10° diameter in cosmic microwave background

Notable theories for CMB Cold Spot: Extreme statistical fluctuation in CMB; imprint caused by cosmic texture topological defect or supervoid on line-of-sight; among others

Anomaly class for CMB Cold Spot: II – Defined purely in terms of quantitatively significant temperature fluctuation; many theories proposed but none fully convincing, many of which would themselves postulate new anomalies, like an extremely large void (class II) or a cosmic texture (class IV)

Notes on anomalous CMB Cold Spot: Existence of giant void along line-of-sight claimed (e.g., Rudnick et al. 2007; Szapudi et al. 2015) and disputed by multiple references (e.g., Smith & Huterer 2010; Granett et al. 2010; Mackenzie et al. 2017)

References for this anomaly in CMB Cold Spot: Cruz et al. (2005, 2008); Szapudi et al. (2015); Mackenzie et al. (2017)

3.3 Class III

Unusual spectrum asteroid: (10537) 1991 RY_{16} [695]

(10537) 1991 RY_{16} *is Solar System source*

Elaboration of anomaly in (10537) 1991 RY_{16}: Basaltic asteroid with unusual spectrum, very unlike V-type asteroids, with a unique 0.63 μm absorption band, orbiting in a gap between the Main Asteroid II and III populations with no sign of parent collisional family.

Notable theories for (10537) 1991 RY_{16}: Related to 349 Dembowska, which is somewhat consistent with spectrum

Anomaly class for (10537) 1991 RY_{16}: 0/III (+ I) – Spectrum shows 0.63 μm absorption band not present in other asteroids, arguably a qualitative feature (III), possible parent body in 349 Bembowska provides possible explanation (0); lack of observed parent family in similar orbits may indicate it has been moved to an unusual location (I).

References for this anomaly in (10537) 1991 RY_{16}: Moskovitz et al. (2008)

Relationships between (10537) 1991 RY_{16} and other Exotica Catalog objects: Orbital primary: Sun [150]

Unexplained geology: Iapetus [547]

Iapetus *is Solar System source*

Elaboration of anomaly in Iapetus: Moon has spectacular ridge encircling much of its equator, with unclear formation mechanism

Notable theories for Iapetus: Both endogeneous and exogeneous models have been proposed, including extensional stress due to rotational braking (Porco et al. 2005) or solid state convection (Czechowski & Leliwa-Kopystyński 2008) and build up of former ring material that has landed on surface (Ip 2006).

Anomaly class for Iapetus: 0/III – Equatorial ridge is unique feature in Solar System (III), although several theories exist to explain its formation (0).
Notes on anomalous Iapetus: Iapetus is famous for its albedo dichomity, with bright trailing hemisphere and dark leading hemisphere. This former anomaly is now explained as the result of dust from the moon Phoebe settling on part of its surface, although the details are unclear (Denk et al. 2010). Iapetus is also abnormally oblate, with a shape that fits a rotation rate about two orders of magnitude faster than now observed (Thomas et al. 2007b; Castillo-Rogez et al. 2007).
References for this anomaly in Iapetus: Porco et al. (2005)
Other references for Iapetus: Denk et al. (2010); Howett et al. (2010); Jet Propulsion Laboratory (2020d)
Relationships between Iapetus and other Exotica Catalog objects: Orbital primary: Saturn [064]

Anomalous interstellar object: 1I/'Oumuamua [068]

1I/'Oumuamua *is Solar System source*
Elaboration of anomaly in 1I/'Oumuamua: Interstellar minor body with no observed activity but nonetheless had non-gravitational accelerations; also had an unusual shape (very prolate or possibly sheet-like).
Notable theories for 1I/'Oumuamua: Depletion in carbon to explain non-detection of dust associated with outgassing responsible for acceleration ('Oumuamua ISSI Team et al. 2019), fragment of tidally disrupted planet (Ćuk 2018) or comet (Raymond et al. 2018; Zhang & Lin 2020) for atypical shape and possibly acceleration, low density debris of interstellar comet disrupted near Sun (Sekanina 2019), fluffball with fractal structure (Moro-Martín 2019), solid H_2 composition (Seligman & Laughlin 2020), ETI artifact (Bialy & Loeb 2018; Loeb 2018)
Anomaly class for 1I/'Oumuamua: III+III – Both the non-gravitational acceleration without observed dusty outgassing (III) and the extreme shape (III) are qualitatively unexpected features; theories exist, but they all are disputed, contrived or problematic.
Notes on anomalous 1I/'Oumuamua: First unambiguous macroscopic interstellar minor body discovered; the velocity of 'Oumuamua was relatively low, perhaps suggesting it is young and not dynamically heated by the Galaxy.
References for this anomaly in 1I/'Oumuamua: Meech et al. (2017); Micheli et al. (2018); Loeb (2018); 'Oumuamua ISSI Team et al. (2019)
Other references for 1I/'Oumuamua: 'Oumuamua ISSI Team et al. (2019); Micheli et al. (2018); Meech et al. (2017)

Relationship to SETI: 1I/'Oumuamua explicitly proposed to be artifact in popular literature (implied in Bialy & Loeb 2018); radio SETI observations completed but no detections (Tingay et al. 2018; Price et al. 2019; Harp et al. 2019)

Anomalous transiters: Boyajian's Star [696]; HD 139139 [697]; VVV-WIT-07 [698]; ASASSN-V J060000.76-310027.83 [699]

Description of anomaly: Stars that display dimming episodes of short–moderate length that qualitatively resemble transits by smaller dark bodies, but for which the occulting bodies are inconsistent with planets or other bodies.
References for anomaly: Schmidt (2019)

Boyajian's Star *is sidereal source*
Boyajian's Star also known as: KIC 8462852, Tabby's Star
Elaboration of anomaly in Boyajian's Star: Deep ($\sim$ 20%), aperiodic eclipses of middle-aged F dwarf (Boyajian et al. 2016) with no infrared excess expected for dusty disk or megastructure (Marengo et al. 2015; Lisse et al. 2015; Thompson et al. 2016), occuring one to several times in episodes separated by hundreds of days; eclipses are chromatic, shallower in red colors, suggesting optically thin dust (Boyajian et al. 2018; Deeg et al. 2018).
Notable theories for Boyajian's Star: Transits of dust clouds associated with minor bodies (e.g., comets during comet shower; Bodman & Quillen 2016), intrinsic stellar variability (Foukal 2017), ETI megastructures; see Wright & Sigurdsson (2016); Wright (2018b)
Anomaly class for Boyajian's Star: 0/III – The depth and aperiodicity of the eclipses are qualitatively unexplained features (III), although models involving circumstellar dust are gaining acceptance due to the color of the eclipses (0).
Notes on anomalous Boyajian's Star: Star also displays unexplained, anomalous variability with timescales of years and longer (see below).
References for this anomaly in Boyajian's Star: Boyajian et al. (2016); Wright & Sigurdsson (2016); Boyajian et al. (2018)
Other references for Boyajian's Star: Montet & Simon (2016); Hippke & Angerhausen (2018); Boyajian et al. (2016); Schaefer (2016); Boyajian et al. (2018); Wright & Sigurdsson (2016)

HD 139139 *is sidereal source*
Elaboration of anomaly in HD 139139: Star with frequent ($\sim 1/3$ day^{-1}) dimming events consistent with being transited at frequent but aperiodic intervals by object(s) of constant size
Notable theories for HD 139139: Intrinsic stellar variability (Rappaport et al. 2019)
Anomaly class for HD 139139: III – Timing of eclipses shows randomness, a qualitatively inexplicable trait (III), no hypotheses have been studied in depth.
Notes on anomalous HD 139139: Star is apparently in binary
References for this anomaly in HD 139139: Rappaport et al. (2019)

VVV-WIT-07 *is sidereal source*
Elaboration of anomaly in VVV-WIT-07: Star that displayed repeated (possibly periodic) deep eclipse, likened to Mamajek's Object and Boyajian's Star
Notable theories for VVV-WIT-07: Eclipse by large circumplanetary ring/disk as in Mamajek's Object, or a similar phenomenon as observed in Boyajian's Star
Anomaly class for VVV-WIT-07: 0/III – Deep dimming episodes generally unexpected feature of star (III), but explanations exist (0)
References for this anomaly in VVV-WIT-07: Saito et al. (2019)

ASASSN-V J060000.76-310027.83 *is sidereal source*
Elaboration of anomaly in ASASSN-V J060000.76-310027.83: Star that had sudden fading episode (Way et al. 2019a), then rebrightened and refaded again (Way et al. 2019b)
Notable theories for ASASSN-V J060000.76-310027.83: Likened to ϵ Aur, in which a circumstellar disk around a companion transits a star, and Boyajian's star by Sokolovsky et al. (2019)
Anomaly class for ASASSN-V J060000.76-310027.83: III – Variability is qualitatively new type (III), too poorly studied to be explained as of yet.
Notes on anomalous ASASSN-V J060000.76-310027.83: Star has no infrared excess (McCollum & Laine 2019a) or secular dimming (Schaefer 2020), dimming may be chromatic indicating optically thin dust (Schaefer 2020).
References for this anomaly in ASASSN-V J060000.76-310027.83: Way et al. (2019a,b); Sokolovsky et al. (2019)

Relationship to SETI: Arnold (2005) proposes anomalous transits by megastructures as possible technosignature. Boyajian's star has been subject of several SETI searches, including radio (Harp et al. 2016) and optical (Abeysekara et al. 2016; Schuetz et al. 2016; Lipman et al. 2019). HD 139139 has published radio SETI observations (Brzycki et al. 2019).

Anomalous spectrum star: WISEA 0615-1247 [700]

References for anomaly: Fajardo-Acosta et al. (2016)

WISEA 0615-1247 *is sidereal source*
Elaboration of anomaly in WISEA 0615-1247: Red dwarf with blue excess emission similar to that expected from a white dwarf but unexpectedly has strong Na I D doublet absorption
Notable theories for WISEA 0615-1247: Triple star system, or chromospheric activity on one star
Anomaly class for WISEA 0615-1247: III – Blue excess emission not found in red dwarfs, and Na I D absorption not found in white dwarfs (III); a few hypotheses speculated about in Fajardo-Acosta et al. (2016) but none examined in detail
Notes on anomalous WISEA 0615-1247: No follow-up study since discovery.

Anomalous non-variable stars: 45 Dra [701]; OGLE LMC-CEP-4506 [702]

Description of anomaly: Stars in variability strip in HR diagram which do not display significant pulsational variability
Anomaly class: III – Lack of variability is qualitative absence of typical behavior (III); generally unexplained and poorly studied

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45 Dra *is sidereal source*
Elaboration of anomaly in 45 Dra: One of Butler (1998) sample of Galactic non-variable stars in Cepheid instability strip and specifically the "restricted" Cepheid instability strips of Fernie (1990) and Chiosi et al. (1992)
Caveats about anomalousness in 45 Dra: Swihart et al. (2017a) report $A_V = 0.831$, implying $M_V = -6.22$ and $B - V = 0.34$, well off the blue edge of instability strip; Kovtyukh et al. (2008) report $E(B - V) = 0.051$, implying $M_V = -5.55$ and $B - V = 0.56$ near the edge of the instability strip

Notes on anomalous 45 Dra: One of Butler (1998) sample that is "stable" in radial velocity in 30 $\mathrm{m\,s^{-1}}$
References for this anomaly in 45 Dra: Fernie & Hube (1971); Butler (1998)

OGLE LMC-CEP-4506 *is sidereal source*
OGLE LMC-CEP-4506 also known as: OGLE-LMC562.05.9009
Elaboration of anomaly in OGLE LMC-CEP-4506: Star nearly identical to Cepheid companion but lacking variability
Notable theories for OGLE LMC-CEP-4506: Could be explained if non-variable companion has misestimated temperature (Gieren et al. 2015), but not confirmed by Pilecki et al. (2018)
Notes on anomalous OGLE LMC-CEP-4506: Non-variable companion is slightly less massive, same temperature
References for this anomaly in OGLE LMC-CEP-4506: Gieren et al. (2015); Pilecki et al. (2018)
Relationships between OGLE LMC-CEP-4506 and other Exotica Catalog objects: Adjacent on sky to (sharing parent object with): 30 Dor [619], CAL 83 nebula [382], Melnick 34 [600], N159F [385], NS 1987A [592], PSR J0537-6910 [586], R136 a1 [566], SN 1987A [375]
Relationships between OGLE LMC-CEP-4506 and objects in I17: Within the sky region occupied by: LMC

Anomalous variable star: LS IV-14 116 [682]

LS IV-14 116 *is sidereal source*
Elaboration of anomaly in LS IV-14 116: Hot helium subdwarf that displays abnormal long-period (g-mode) variability, despite lying in the p-mode instability strip where periods are expected to be short
Notable theories for LS IV-14 116: Variability caused by ϵ mechanism, in which rate of nuclear burning fluctuates – according to Randall et al. (2015), this is only expected to happen if LS IV-14 116 has not yet settled on the helium main sequence while atmospheric models indicate it has; Battich et al. (2018) could only account for the shortest modes with the ϵ mechanism.
Anomaly class for LS IV-14 116: III – Star pulsates through unexpected and unknown mechanism (III); explanations not consistent with observations of star as of yet.
Notes on anomalous LS IV-14 116: Star also has abnormal abundances of germanium, strontium, yttrium, and zirconium (Naslim et al. 2011) (see above)
References for this anomaly in LS IV-14 116: Green et al. (2011); Randall et al. (2015)
Other references for LS IV-14 116: Randall et al. (2015); Naslim et al. (2011); Green et al. (2011)

Anomalous dimming star: Boyajian's Star [696]; EK Dra [703]; ASASSN-V J190917.06+182837.36 [704]; ASASSN-V J213939.3-702817.4 [705]; ASASSN V J193622.23+115244.1 [706]

Description of anomaly: Stars that undergo unexplained gradual dimmings (generally with re-brightenings to original luminosity).

Boyajian's Star *is sidereal source*
Elaboration of anomaly in Boyajian's Star: Unexplained years-long (possibly decades-long) dimming and brightening by several percent (Montet & Simon 2016), with no excess infrared emission as expected from circumstellar dust (Marengo et al. 2015; Lisse et al. 2015; Thompson et al. 2016)
Notable theories for Boyajian's Star: Circumstellar dust obscuration, intrinsic stellar variability, interstellar dust obscuration, post-merger event, see Wright & Sigurdsson (2016)
Anomaly class for Boyajian's Star: III – Years-long dimming by several percent nearly unprecedented for F dwarfs (III), remains essentially unexplainable, especially without an infrared excess.
Notes on anomalous Boyajian's Star: Schaefer (2016) first claimed the star was dimming over the past century, although this was vigorously disputed by Hippke et al. (2016); Montet & Simon (2016) revealed much more rapid dimming in *Kepler* light curve; subsequent photometry indicates re-brightening over several years, although variability on long timescales is still unclear; secular variability possibly chromatic (Meng et al. 2017).
References for this anomaly in Boyajian's Star: Schaefer (2016); Montet & Simon (2016); Wright & Sigurdsson (2016); Hippke & Angerhausen (2018)
Other references for Boyajian's Star: Montet & Simon (2016); Boyajian et al. (2016); Schaefer (2016); Wright & Sigurdsson (2016); Hippke & Angerhausen (2018); Boyajian et al. (2018)

EK Dra *is sidereal source*
Elaboration of anomaly in EK Dra: Young sun analog that has been fading for ~ 50 yr
Anomaly class for EK Dra: III – Years-long dimming qualitatively reminiscent of Boyajian's Star (III), although EK Dra is

young; very little theoretical work

Notes on anomalous EK Dra: The star also has a nine year magnetic cycle superimposed on the secular dimming; secular fading rate: 0.0017 mag yr^{-1} in 1958–1975, 0.0057 mag yr^{-1} in 1975–2002 (Fröhlich et al. 2002); brief pause in 2006–2007 before resuming in 2010 (Järvinen et al. 2018)

References for this anomaly in EK Dra: Fröhlich et al. (2002); Järvinen et al. (2005, 2018)

ASASSN-V J190917.06+182837.36 *is sidereal source*

Elaboration of anomaly in ASASSN-V J190917.06+182837.36: Star dimmed by 1 magnitude over a few days.

Anomaly class for ASASSN-V J190917.06+182837.36: III – Dimming episode's existence is anomalous (III); too poorly studied to be explained.

Notes on anomalous ASASSN-V J190917.06+182837.36: McCollum & Laine (2019b) finds excess absorption, suggesting circumstellar material, $T_{\rm eff} = 6{,}000$ K, $L \sim 60$ $L_{\odot}$

References for this anomaly in ASASSN-V J190917.06+182837.36: Way et al. (2019c)

ASASSN-V J213939.3-702817.4 *is sidereal source*

ASASSN-V J213939.3-702817.4 also known as: Gaia DR2 4315228344710978816

Elaboration of anomaly in ASASSN-V J213939.3-702817.4: Star dimmed by over 1 magnitude over a few days, then recovered luminosity just as rapidly.

Anomaly class for ASASSN-V J213939.3-702817.4: III – Dimming episode's existence is anomalous (III); too poorly studied to be explained.

Notes on anomalous ASASSN-V J213939.3-702817.4: McCollum & Laine (2019c) finds substantial excess absorption, indicating circumstellar material, $T_{\rm eff} = 6{,}800$ K, consistent with F0V dwarf, no MIR excess detected by WISE

References for this anomaly in ASASSN-V J213939.3-702817.4: Way et al. (2020)

ASASSN V J193622.23+115244.1 *is sidereal source*

Elaboration of anomaly in ASASSN V J193622.23+115244.1: Star dimmed by 1.5 mag over the course of a week

Notes on anomalous ASASSN V J193622.23+115244.1: Star has had smaller 0.5 mag dimming episodes in past; Way et al. (2020) find L: 9.31 $L_{\odot}$, $T_{\rm eff}$: 6,341 K

Vanishing supergiants: NGC 6946-BH1 [275]; NGC 3021-CANDIDATE 1 [707]

Description of anomaly: Supergiant stars that have faded and disappeared, far below initial luminosity, possibly after minor outbursts

Notable theories for anomaly: Presumably related to failed supernovae resulting in black holes (see Prototypes)

References for anomaly: Kochanek et al. (2008)

Anomaly class: 0/III – Supergiants have not previously been observed to vanish without a supernova (III), but failed supernovae provide a ready explanation for their disappearance (0).

NGC 6946-BH1 *is sidereal source*

Notes on anomalous NGC 6946-BH1: First candidate discovered (Gerke et al. 2015), later observations confirm the progenitor is faded or missing (Adams et al. 2017; Basinger et al. 2020); Humphreys (2019) speculates progenitor was a yellow hypergiant

References for this anomaly in NGC 6946-BH1: Gerke et al. (2015); Adams et al. (2017)

Other references for NGC 6946-BH1: Adams et al. (2017); Gerke et al. (2015)

Relationships between NGC 6946-BH1 and other Exotica Catalog objects: Adjacent on sky to (sharing parent object with): SN 2008S [756]

Relationships between NGC 6946-BH1 and objects in I17: Within the sky region occupied by: NGC 6946

NGC 3021-CANDIDATE 1 *is sidereal source*

References for this anomaly in NGC 3021-CANDIDATE 1: Reynolds et al. (2015)

Other references for NGC 3021-CANDIDATE 1's host: Jang & Lee (2017)

Anomalous stellar outburst: BW Vul [708]; BD +31°1048 [709]; AQ CVn [710]; β Cam [711]; V654 Her [712]; PTF 14jg [713]; ASASSN-19lb [714]; ASASSN-20lj [715]

BW Vul *is sidereal source*

Elaboration of anomaly in BW Vul: B giant star with unexplained 0.8 mag amplitude, rose over ~ 10 s and persisted for an hour before fading over ~ 15 min

Anomaly class for BW Vul: III – Remains unexplained and large flares not expected of early-type stars (III)
Notes on anomalous BW Vul: Listed in Schaefer (1989)
References for this anomaly in BW Vul: Eggen (1948); Schaefer (1989)
Other references for BW Vul: Stankov et al. (2003); Fokin et al. (2004)

BD +31°1048 *is sidereal source*
Elaboration of anomaly in BD +31° 1048: Unexplained 3 mag outburst or flare in B dwarf occurring over several days
Notable theories for BD +31° 1048: The flare may have occurred on an undetected M dwarf companion
Anomaly class for BD +31° 1048: III – Remains unexplained and large flares not expected of early-type stars (III)
Notes on anomalous BD +31° 1048: Listed in Schaefer (1989)
References for this anomaly in BD +31° 1048: Andrews (1964); Schaefer (1989); Andrews (1996)

AQ CVn *is sidereal source*
AQ CVn also known as: SS 199 II
Elaboration of anomaly in AQ CVn: A dwarf with ~ 2.4 mag outburst lasting several minutes
Anomaly class for AQ CVn: III – Unexplained flare not expected of A dwarfs (III)
Notes on anomalous AQ CVn: Listed in Schaefer (1989)
References for this anomaly in AQ CVn: Philip (1968); Schaefer (1989)
Other references for AQ CVn: Brown et al. (2008)

β **Cam** *is sidereal source*
Elaboration of anomaly in β Cam: Unexplained < 0.25 s flash from G supergiant
Anomaly class for β Cam: III – Unexplained flash not expected from supergiant stars (III)
Notes on anomalous β Cam: Wdowiak & Clifton (1985) reports it attained a peak brightness of $m_B \sim 3$, implying a 2 mag amplitude; β Cam is a visual (apparent) binary with an unrelated subgiant, with the supergiant itself apparently lacking a companion (e.g., Burki & Mayor 1983; McAlister et al. 1989); listed in Schaefer (1989), which lists subgiant as possible companion/source
References for this anomaly in β Cam: Wdowiak & Clifton (1985); Schaefer (1989)
Other references for β Cam: Lyubimkov et al. (2010)

V654 Her *is sidereal source*
Elaboration of anomaly in V654 Her: Unexplained minutes-long outburst in K giant
Anomaly class for V654 Her: III – Flare remains unexplained phenomenon (III)
Notes on anomalous V654 Her: Outburst in 1973, with ~ 0.1 mag amplitude (Moffett & Vanden Bout 1973); classified as K dwarf in Moffett & Vanden Bout (1973) but later identified as K giant (Tsvetkov & Pettersen 1985); giant classification supported by *Gaia* distance; listed in Schaefer (1989)
References for this anomaly in V654 Her: Moffett & Vanden Bout (1973); Schaefer (1989)
Other references for V654 Her: Tsvetkov & Pettersen (1985); Bailer-Jones (2011)

PTF 14jg *is sidereal source*
Elaboration of anomaly in PTF 14jg: FU Ori-like stellar outburst, with rise by $\sim$ 6–7 magnitudes, then faded by 3 magnitude to "plateau"
Notable theories for PTF 14jg: FU Ori outburst (enhanced accretion onto young star), although unusually hot and bright
Anomaly class for PTF 14jg: 0/III – Stellar outburst of type not seen before (III), although FU Ori mechanism provides explanation (0); could be interpreted as class II because differences might be attributed to temperature of outburst
Notes on anomalous PTF 14jg: Star displays variable spectral type and spectroscopic evidence of outflow
References for this anomaly in PTF 14jg: Hillenbrand et al. (2019)

ASASSN-19lb *is sidereal source*
Elaboration of anomaly in ASASSN-19lb: Star with unexplained outburst and variability
Anomaly class for ASASSN-19lb: III – Outburst qualitatively abnormal (III), unexplained
Notes on anomalous ASASSN-19lb: Star originally at $g \sim 15.6$ faded to 16.3 and erupted to 14.8 over eleven weeks; *Gaia* DR2 lists $L = 1.1\ L_\odot$, $T_{\text{eff}} = 6{,}600$ K, implying dwarf star (Gaia Collaboration et al. 2018b)
References for this anomaly in ASASSN-19lb: Jayasinghe et al. (2019)

ASASSN-20lj *is sidereal source*
Elaboration of anomaly in ASASSN-20lj: Unexplained ~ 2 mag outburst in Sun-like star

Anomaly class for ASASSN-20lj: III – Outburst qualitatively abnormal (III), unexplained
Notes on anomalous ASASSN-20lj: *Gaia* DR2 lists L = 0.88 $L_\odot$, $T_{\rm eff}$ = 5,400 K (Gaia Collaboration et al. 2018b)
References for this anomaly in ASASSN-20lj: Denisenko (2020)

Complex magnetic star: Landstreet's Star [717]

Landstreet's Star *is sidereal source*
Landstreet's Star also known as: HD 37776, V901 Ori
Elaboration of anomaly in Landstreet's Star: Young magnetic chemically peculiar star with unusually complex magnetic field geometry with non-axisymmetric, non-dipolar components dominant (Thompson & Landstreet 1985; Kochukhov et al. 2011); complex light curve; decadal rotational period variability, including fastest rotational braking observed (Mikulášek et al. 2008)
Notable theories for Landstreet's Star: Complex fossil magnetic field, with relatively stable configuration; complex light curve due to surface abundance variations (Krtička et al. 2007; Kochukhov et al. 2011)
Anomaly class for Landstreet's Star: 0/III – Magnetic field geometry is qualitatively unusual in its complexity (III), although some partial hypotheses exist and the star seems to be just an extreme example of magnetic chemically peculiar stars (0).
References for this anomaly in Landstreet's Star: Mikulášek et al. (2020)

Further examples of anomaly: τ Sco, σ Ori E, CU Vir

Hybrid gamma-ray bursts: GRB 060614 [718]; GRB 060505 [719]

Description of anomaly: Gamma-ray bursts with some properties reminiscent of long-soft GRBs and some like short-hard GRBs

GRB 060614 *is sidereal source*
Elaboration of anomaly in GRB 060614: Peculiar nearby long-duration GRB with no identified supernova; had initial 5 s long spike of hard radiation followed by tail of soft emission with $T_{90} \sim 100$ s
Notable theories for GRB 060614: Short-hard gamma-ray burst, supported by apparent identification of macronova "bump" in light curve (Yang et al. 2015)
Anomaly class for GRB 060614: 0/III/IV – Historically, this GRB has defied classification (IV) as it displays some behaviors of long GRBs and some of short GRBs, particularly lacking the supernova that should be seen with a long GRB (III); however, the macronova signature would imply an identification as a (peculiar) short GRB (0)
Notes on anomalous GRB 060614: Host redshift: 0.125 (Gal-Yam et al. 2006)
References for this anomaly in GRB 060614: Della Valle et al. (2006); Gehrels et al. (2006); Gal-Yam et al. (2006); Yang et al. (2015)

GRB 060505 *is sidereal source*
Elaboration of anomaly in GRB 060505: Peculiar intermediate-duration ($T_{90} = 4$ s) GRB with no identified supernova
Notable theories for GRB 060505: Peculiar long GRB resulting from collapsar with reduced supernova (McBreen et al. 2008)
Anomaly class for GRB 060505: 0/III/IV – Other characteristics imply it is indeed a peculiar long GRB (0), although the lack of a supernova is hard to reconcile (III), and might indicate a new object class (IV)
Notes on anomalous GRB 060505: Spectral lag implies it is a long GRB (McBreen et al. 2008); found in a low metallicity massive star formation region, which is consistent with massive star origin of long GRBs (McBreen et al. 2008; Thöne et al. 2014)
References for this anomaly in GRB 060505: Ofek et al. (2007); McBreen et al. (2008); Thöne et al. (2014)

Anomalous stellar flare star: YZ CMi [716]

Notes on anomaly: Apparent stellar flares solely in potassium lines were observed in HD 117043, but were most likely the result of matches in the observatory (Wing et al. 1967)

YZ CMi *is sidereal source*
Elaboration of anomaly in YZ CMi: Star observed to have stellar flares with unidentified spectral lines
Anomaly class for YZ CMi: III – New spectral features not present in typical stellar flares
Notes on anomalous YZ CMi: Unidentified lines observed at 4007 and 4276 Å; the star itself is very well studied, but these flares have not been followed up on in the literature

References for this anomaly in YZ CMi: Haisch & Glampapa (1985)
YZ CMi in I17

Fast radio burster: SGR 1935+2154 [269]

Notes on anomaly: Extragalactic fast radio bursts (FRBs) are also included as Class IV anomalies, under the presumption they may represent several classes of objects

SGR 1935+2154 *is sidereal source*
SGR 1935+2154 also known as: FRB 200428 (transient)
Elaboration of anomaly in SGR 1935+2154: Galactic magnetar that emitted brilliant millisecond radio transient, of similar luminosity and duration to extragalactic FRBs
Notable theories for SGR 1935+2154: Several magnetar FRB theories, including magnetar hyperflares (Popov & Postnov 2010) and asteroid impacts on magnetars (Dai & Zhong 2020); see Platts et al. (2019) for more discussion.
Anomaly class for SGR 1935+2154: III – This is the one FRB with a confident association (not class IV), although it seems likely that many or all of the others are also magnetars; although many hypotheses exist for the mechanism, at present the reason for the unusual FRB phenomenon is unknown (III).
Notes on anomalous SGR 1935+2154: Fainter radio bursts observed (Zhang et al. 2020; Kirsten et al. 2020), also observed to emit X-ray/gamma-ray flares as soft gamma repeater, including one event associated with FRB 200428 itself (Mereghetti et al. 2020)
References for this anomaly in SGR 1935+2154: Scholz & Chime/Frb Collaboration (2020); Bochenek et al. (2020); Mereghetti et al. (2020)
Other references for SGR 1935+2154: Mereghetti et al. (2020); Scholz & Chime/Frb Collaboration (2020); Bochenek et al. (2020)

Swooshing pulsar: PSR B0919+06 [720]

Description of anomaly: Pulsar with quasiperiodic episodes during which radio pulses drift
Notes on anomaly: Also observed in PSR 1859+07 (Rankin et al. 2006)
Notable theories for anomaly: May result from companion affecting pulsar timing (disfavored by LOFAR; Shaifullah et al. 2018), variable absorption, intrinsically variable emission
References for anomaly: Rankin et al. (2006); Wahl et al. (2016)
Anomaly class: III – Qualitatively abnormal phenomenon for radio pulsars (III), largely unexplained

PSR B0919+06 *is sidereal source*
Other references for PSR B0919+06: Manchester et al. (2005)

Anomalous variable millisecond pulsar-white dwarf binary: PSR J1911-5958A [665]

PSR J1911-5958A *is sidereal source*
Elaboration of anomaly in PSR J1911-5958A: Millisecond pulsar-white dwarf binary with inexplicable optical light curve, with pronounced peaks ($\gtrsim 0.2$ mag) near quadruture
Anomaly class for PSR J1911-5958A: III – Qualitatively different light curve from expectation where pulsar heats white dwarf hemisphere and other explanations (III), with white dwarf too low mass for variability to be attributed to pulsations or magnetism
Notes on anomalous PSR J1911-5958A: System is also located very far from center of host globular cluster NGC 6752 (see above); white dwarf mass: 0.180 ± 0.018 $M_\odot$ (Corongiu et al. 2012)
References for this anomaly in PSR J1911-5958A: Cocozza et al. (2006)
Other references for PSR J1911-5958A: Cocozza et al. (2006); Ferraro et al. (2003a); Colpi et al. (2003)
Relationships between PSR J1911-5958A and other Exotica Catalog objects: Within the sky region occupied by: NGC 6752 [340]

Red flaring cataclysmic variable/young stellar object: DDE 168 [721]

DDE 168 *is sidereal source*
Elaboration of anomaly in DDE 168: Extremely red (in *Gaia* photometry) star with unexplained optical flare (0.7 magnitude)

Anomaly class for DDE 168: II/III(/IV) – The color index is anomalously high (II), and the optical flare is also unexplained (III); the counterpart is not identified beyond being stellar and hypothetically could represent a new type (IV), although it seems likely to be a young stellar object to Larin 2.

Notes on anomalous DDE 168: Gaia color index: $BP - RP = 3.27$; Similar to Larin 2, which Larin et al. (2018) proposed was an anomalous cataclysmic variable, but Oliveira et al. (2020) identifies it as a T Tauri star; Denisenko (2019) claim that DDE 168 has a similar parallax and proper motion to Larin 2, suggesting association; in field of Seyfert galaxy NGC 4945

References for this anomaly in DDE 168: Denisenko (2019)

Dynamically-peculiar globular cluster: NGC 6752 [340]

NGC 6752 *is sidereal source*

Elaboration of anomaly in NGC 6752: Globular cluster with three millisecond pulsar systems near core observed to have anomalous accelerations and two millisecond pulsar system abnormally far from center

Notable theories for NGC 6752: Unusual dynamics (including accelerations) due to central black hole binary or intermediate mass black hole (D'Amico et al. 2002)

Anomaly class for NGC 6752: 0/III (I) – Globular cluster has unusual dynamics (III) – could be interpreted as each pulsar system having unusual location or kinematics (I; see also PSRJ1911-5958A, in this cluster) – but possible explanation from central black hole(s)

References for this anomaly in NGC 6752: D'Amico et al. (2002); Ferraro et al. (2003b)

Other references for NGC 6752: Mackey & van den Bergh (2005); Forbes & Bridges (2010); Dinescu et al. (1999); Baumgardt & Hilker (2018)

Relationships between NGC 6752 and other Exotica Catalog objects: Contains within projected sky region: PSR J1911-5958A [665]

Galactic holes: UMi dSph [722]; NGC 247 [723]

Description of anomaly: Galaxies with unexplained underdensities of stars

UMi dSph *is sidereal source*

Elaboration of anomaly in UMi dSph: Center of galaxy apparently with "void" lacking stars in its center (Battinelli & Demers 1999), with no infrared excess expected from dust (Demers & Battinelli 2001)

Notable theories for UMi dSph: Bellazzini et al. (2002) claims the "void" is artifact of off-center peak of the stellar density

Anomaly class for UMi dSph: 0/III – A true hole in a galactic center would be a qualitatively new feature (III), but the anomaly's existence is questionable (0)

Notes on anomalous UMi dSph: Olszewski & Aaronson (1985) claimed UMi dSph was clumpy, kicking off a long debate on the existence of substructure in the galaxy; Pace et al. (2014) notes that many dwarf spheroidals have substructures, as a result of their formation, finding evidence for UMi dSph specifically

References for this anomaly in UMi dSph: Battinelli & Demers (1999); Demers & Battinelli (2001); Bellazzini et al. (2002)

UMi dSph in I17

NGC 247 *is sidereal source*

Elaboration of anomaly in NGC 247: Pronounced multi-kiloparsec wide void in young stars and HI to one side of galactic disk, apparently not due to star formation feedback.

Notable theories for NGC 247: Possibly created by impact of dark matter subhalo on galactic disk (Wagner-Kaiser et al. 2014; Shah et al. 2019)

Anomaly class for NGC 247: III – The hole is not evidently related to any known phenomenon, indicating it is a qualitatively new phenomenon in galaxies

Notes on anomalous NGC 247: The hole, with a diameter of over 3 kpc, is easily visible on photographs, and has been known about for over a century (Roberts 1915). Wagner-Kaiser et al. (2014) find a dearth of stars younger than 1 Gyr in the void. Very little recent theoretical work exists for this anomaly.

References for this anomaly in NGC 247: Wagner-Kaiser et al. (2014)

Relationship to SETI: Large "holes" in galaxies are a generic expected feature if we observe one containing an incomplete expanding ETI that covers stars in Dyson spheres, but generally we expect to observe infrared waste heat from the cloaked stars, which is not observed (Zackrisson et al. 2015).

Variable galaxy: Leoncino Dwarf [724]

Leoncino Dwarf *is sidereal source*
Elaboration of anomaly in Leoncino Dwarf: Dwarf galaxy hosting an unknown optical transient, possibly shifting in position or morphology over forty years as well
Notable theories for Leoncino Dwarf: Filho & Sánchez Almeida (2018) suggest the only phenomenon that might account for the anomaly is lensing by a dark matter halo or black hole, although these events are expected to be too rare.
Anomaly class for Leoncino Dwarf: III/IV/V – If the transient is viewed as an aspect of the galaxy, it is a completely unknown one (III), and large-scale changes of position or morphology violate causality (V); alternatively, the anomaly may be local, in which case it is a new type of transient (IV); no satisfactory explanation exists yet.
Notes on anomalous Leoncino Dwarf: No follow-up has been conducted as far as we are aware.
References for this anomaly in Leoncino Dwarf: Filho & Sánchez Almeida (2018)

Anomalous flaring active galactic nucleus: Spikey [725]; ZTF19abanrhr [726]

Spikey *is sidereal source*
Spikey also known as: KIC 11606854
Elaboration of anomaly in Spikey: AGN that displayed a previously unknown days-long time-symmetric optical outburst
Notable theories for Spikey: Self gravitational lensing by a companion supermassive black hole (Hu et al. 2020)
Anomaly class for Spikey: 0/III – The flare is inconsistent with a tidal disruption event and the symmetric light curve is novel (III), but self-lensing provides a natural explanation (0)
References for this anomaly in Spikey: Smith et al. (2018); Hu et al. (2020)

ZTF19abanrhr *is sidereal source*
Elaboration of anomaly in ZTF19abanrhr: Weeks-long single AGN optical flare; identified as possible counterpart to GW 190521 (=S190521g), the merger of two unusually massive black holes
Notable theories for ZTF19abanrhr: Electromagnetic flare from GW 190521 event, occurred when two (large) stellar-mass black holes merged in the environment of an AGN (Graham et al. 2020); may be a microlensing event (De Paolis et al. 2020)
Anomaly class for ZTF19abanrhr: 0/III – Flare appears to be new phenomenon associated with AGNs (III), and would be new (but explainable) phenomenon associated with black hole mergers if actually associated with GW 190521 (0/III), but could be mundane microlensing event
References for this anomaly in ZTF19abanrhr: Graham et al. (2020); De Paolis et al. (2020)

Quasi-periodic erupting active galactic nucleus: GSN 069 [727]

GSN 069 *is sidereal source*
Elaboration of anomaly in GSN 069: AGN that experiences hour-long X-ray flares (luminosity increase by ~ 100) that recur at regular (nine hour) intervals
Notable theories for GSN 069: Repeated episodes of accretion from white dwarf on nine hour eccentric orbit around black hole (King 2020)
Anomaly class for GSN 069: III – The regular recurrence and brightness of the outbursts implies a new phenomenon at work in this AGN
References for this anomaly in GSN 069: Miniutti et al. (2019)

Further examples of anomaly: RX J1301.9+2747 (Giustini et al. 2020)

Coherently variable active galactic nucleus: MCG+00-09-070 [728]

MCG+00-09-070 *is sidereal source*
Elaboration of anomaly in MCG+00-09-070: AGN with claimed coherent picosecond optical variability, as inferred from spectral features
Anomaly class for MCG+00-09-070: III – Variability of this sort has never been observed in an AGN before, and it would be a new phenomenon
Notes on anomalous MCG+00-09-070: The galaxy corresponds to the coordinates given for the galaxy considered in Figure 1 of Borra (2013); no other coordinates or specific objects are given. The method for detecting the variability is based on

the appearance of combs of evenly spaced lines if repeating pulses are coherent (exactly identical in time, down to phases, except translated; Borra 2010). This method has been also used to claim coherent picosecond variability in stars as a detected technosignature (see below; Borra & Trottier 2016), although that result is very controversial and the method may be subject to uncharacterized systematics (Isaacson et al. 2019; Hippke 2019).
References for this anomaly in MCG+00-09-070: Borra (2013)

3.4 Class IV

Unidentified radio sources: 3C 141 [729]; 3C 125 [730]; 3C 431 [731]; PMN J1751-2524 [732]; FRB 121102 [733]

Notable theories for anomaly: Obscured radio galaxies (3C 125, 3C 141, 3C 431 in Spinrad et al. 1985), although not confirmed and no infrared counterparts found for these in WISE (Maselli et al. 2016)
Anomaly class: IV – Unassociated with object of known type.

3C 141 *is sidereal source*
Elaboration of anomaly in 3C 141: Bright radio source with possible unidentified optical counterpart
Notable theories for 3C 141: Martel et al. (1998): four possible optical counterparts found, one optical point source favored
Notes on anomalous 3C 141: No *Swift* X-ray or WISE infrared counterparts (Maselli et al. 2016)
References for this anomaly in 3C 141: Martel et al. (1998); Maselli et al. (2016)

3C 125 *is sidereal source*
Elaboration of anomaly in 3C 125: Bright radio source with no counterparts
References for this anomaly in 3C 125: Maselli et al. (2016)

3C 431 *is sidereal source*
Elaboration of anomaly in 3C 431: Bright radio source with no counterparts
References for this anomaly in 3C 431: Maselli et al. (2016)

PMN J1751-2524 *is sidereal source*
Elaboration of anomaly in PMN J1751-2524: Radio source with no likely counterparts
Notes on anomalous PMN J1751-2524: Titov et al. (2011) finds an optical point source near its position, which is unlikely to be an AGN due to heavy expected Galactic dust extinction; used frequently as a phase calibrator
References for this anomaly in PMN J1751-2524: Titov et al. (2011)

FRB 121102 *is sidereal source*
Elaboration of anomaly in FRB 121102: Unexplained radio counterpart to repeating fast radio burst; variable at 10% level
Notable theories for FRB 121102: Shock in magnetar wind nebula (Metzger et al. 2017; Margalit & Metzger 2018); shocks in progenitor's supernova interacting with surrounding material (Metzger et al. 2017)
Anomaly class for FRB 121102: 0/IV/III – Has not been positively identified (IV), although could be related to magnetars if that is the nature of FRB 121102 (III), and theories exist for its nature (0)
Notes on anomalous FRB 121102: FRB 121102 is the first known repeating FRB and the first with a confidently associated host galaxy; located within a star-forming region in a star-forming dwarf galaxy, which favors a progenitor associated with young/massive stars (including magnetars) (Tendulkar et al. 2017; Bassa et al. 2017b)
References for this anomaly in FRB 121102: Chatterjee et al. (2017); Margalit & Metzger (2018)
Other references for FRB 121102: Tendulkar et al. (2017); Bassa et al. (2017b); Chatterjee et al. (2017); Spitler et al. (2016)

Odd radio circles: ORC 2 [734]

Description of anomaly: Unexplained disk-shaped arcminute-scale radio sources far from Galactic plane
Notable theories for anomaly: Remnant bubble of unknown type of transient; population inconsistent with known source populations like supernova remnants
References for anomaly: Norris et al. (2021)
Anomaly class: IV – Apparently, completely new type of radio source

ORC 2 *is sidereal source*
ORC 2 also known as: EMU PD J205842.8-573658
Notes on anomalous ORC 2: ORC 2 is adjacent to the much fainter ORC 3, also coincident with radio galaxy (lobes denoted as sources A and B in Norris et al. 2021) and also a galaxy (source C in Norris et al. 2021)

Radio filament: Galactic Center Radio Arc [735]

Description of anomaly: Unexplained narrow, long synchrotron-emitting filaments found in Galactic Center region
Notable theories for anomaly: Cosmic ray electrons of unknown origin confined along magnetic field lines – possible electron sources include ionized surface of a molecular cloud (Serabyn & Morris 1994), an H II region (Uchida et al. 1996), star clusters (Yusef-Zadeh 2003), and dark matter annihilation (Linden et al. 2011); distortions in magnetic field (Dahlburg et al. 2002)
References for anomaly: Morris (1996); LaRosa et al. (2004)
Anomaly class: IV – Nature of these features remain unknown, despite several theories

Galactic Center Radio Arc *is sidereal source*
Notes on anomalous Galactic Center Radio Arc: The Radio Arc is by far the most prominent, as a bundle of thinner nonthermal filaments; assumed distance is the same as Sgr A* (8,178 pc; Gravity Collaboration et al. 2019b)
References for this anomaly in Galactic Center Radio Arc: Yusef-Zadeh et al. (1984); Yusef-Zadeh & Morris (1987); Anantharamaiah et al. (1991)

Unidentified gamma-ray sources: 3FGL J1539.2-3324 [736]; 3FGL J1231.6-5113 [737]

Description of anomaly: Unassociated GeV gamma-ray sources found off Galactic plane
Notable theories for anomaly: In the past, many unassociated sources have turned out to be spider pulsars (Romani 2012; Salvetti et al. 2017)

3FGL J1539.2-3324 *is sidereal source*
Notable theories for 3FGL J1539.2-3324: Possible association with the blazar NVSS J153911-332209 (Ackermann et al. 2015), WISE J153911.79-332211.4 (Schinzel et al. 2015)
Anomaly class for 3FGL J1539.2-3324: 0/IV – No secure association (IV), but plausibly a blazar (0).
Notes on anomalous 3FGL J1539.2-3324: Galactic latitude: +17°; radio and infrared counterpart in Schinzel et al. (2015) and Ackermann et al. (2015), but no X-ray or optical counterpart in Salvetti et al. (2017); no "refined" association in Massaro et al. (2015)
References for this anomaly in 3FGL J1539.2-3324: Massaro et al. (2015); Salvetti et al. (2017)

3FGL J1231.6-5113 *is sidereal source*
Anomaly class for 3FGL J1231.6-5113: IV – No secure, classified counterpart
Notes on anomalous 3FGL J1231.6-5113: Galactic latitude: +11°; possible X-ray counterparts in Acero et al. (2013), but otherwise considered "intriguing" and unidentified; possible radio and infrared counterparts in Schinzel et al. (2015); no "refined" association in Massaro et al. (2015)
References for this anomaly in 3FGL J1231.6-5113: Acero et al. (2013); Massaro et al. (2015)

Dark accelerator: TeV J2032+4130 [738]; HESS J1745-303 [739]

Description of anomaly: Unassociated TeV gamma-ray source near Galactic Plane, presumably illuminated by freshly accelerated cosmic rays

TeV J2032+4130 *is sidereal source*
Notable theories for TeV J2032+4130: Pulsar wind nebula (Aliu et al. 2014)
Anomaly class for TeV J2032+4130: 0/IV – Association with known source type insecure and historically unidentified (IV), but may be a pulsar wind nebula (0).
Notes on anomalous TeV J2032+4130: Most cited unidentified TeV source discussed in Aharonian et al. (2008); within but off center from Cygnus Cocoon, near PSR J2032+4130
References for this anomaly in TeV J2032+4130: Aharonian et al. (2002, 2008); Aliu et al. (2014)
Relationships between TeV J2032+4130 and other Exotica Catalog objects: Within the sky region occupied by: Cygnus Cocoon [387]; Adjacent on sky to (sharing parent object with): Cyg OB2 [346]

HESS J1745-303 *is sidereal source*
Elaboration of anomaly in HESS J1745-303: Dark accelerator contains three subregions, (A, B, and C)
Notable theories for HESS J1745-303: Region A appears to be a molecular cloud illuminated by cosmic ray collisions with cosmic rays source possibly SNR G359.1-0.5 (Aharonian et al. 2008; Hayakawa et al. 2012; Hui et al. 2016), but other regions too far from supernova remnant

Anomaly class for HESS J1745-303: IV – Remains unidentified (IV); although A may have an association with supernova remnant, B and C not explained

References for this anomaly in HESS J1745-303: Aharonian et al. (2008); Hayakawa et al. (2012); Hui et al. (2016)

Unidentified radio transients: LWAT 171018 [740]; ILT J225347+862146 [741]; TGSSADR J183304.4-384046 [742]; J103916.2+585124 [743]; WJN J1443+3439 [744]; 43.78+59.3 [745]; FIRST J141918.9+394036 [746]; RT 19920826 [747]

Description of anomaly: Events in which an unknown source radiates detectable radio emission for a limited time and then fades below sensitivity

Notable theories for anomaly: Some may be instrumental artifacts (Frail et al. 2012; Aoki et al. 2014); radio transients have been predicted from old neutron stars (Ofek et al. 2010) and explosive events (Metzger et al. 2015); the brightest authentic radio transients likely involve coherent emission through some plasma process

References for anomaly: Fender & Bell (2011); Frail et al. (2012); Anderson et al. (2019b)

Anomaly class: IV – With the exception of FIRST J141918.9+394036, none of the sources have been identified

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LWAT 171018 *is sidereal source*

Elaboration of anomaly in LWAT 171018: Sub-minute (15–20 s) low frequency (34 MHz) radio transient

Notes on anomalous LWAT 171018: Detected by two ground stations of Long Wavelength Array; flux was 842 ± 116 Jy, 830 ± 92 Jy

References for this anomaly in LWAT 171018: Varghese et al. (2019)

ILT J225347+862146 *is sidereal source*

Elaboration of anomaly in ILT J225347+862146: Minutes-long low frequency (60 MHz) radio transient

Notes on anomalous ILT J225347+862146: Detected in a single epoch image of the North Celestial Pole by the Low Frequency Array; integration time 11 min; flux $\sim 20 \pm 5$ Jy

References for this anomaly in ILT J225347+862146: Stewart et al. (2016)

TGSSADR J183304.4-384046 *is sidereal source*

Elaboration of anomaly in TGSSADR J183304.4-384046: Long duration (single-epoch) low frequency (150 MHz) radio transient

Notes on anomalous TGSSADR J183304.4-384046: Detected in single epoch of TGAS images, with integration time of 15 min, but had vanished within three years, so timescale between minutes and years; flux: 182 ± 26 mJy (147.5 MHz)

References for this anomaly in TGSSADR J183304.4-384046: Murphy et al. (2017)

J103916.2+585124 *is sidereal source*

Elaboration of anomaly in J103916.2+585124: Several hour long low frequency (325 MHz) radio transient

Notes on anomalous J103916.2+585124: Detected in Very Large Array archival images; flux: 2.1 mJy

References for this anomaly in J103916.2+585124: Jaeger et al. (2012)

WJN J1443+3439 *is sidereal source*

Elaboration of anomaly in WJN J1443+3439: Several day long 1.42 GHz radio transient

Notes on anomalous WJN J1443+3439: Detected in two epochs separated by a day with the Waseda Nasu Pulsar Observatory, lasted < 72 hr; of the transients detected by the Observatory, this was the one that passed reliability checks in Aoki et al. (2014); flux: 1.5, 3.0 Jy; existence not certain

References for this anomaly in WJN J1443+3439: Niinuma et al. (2007); Aoki et al. (2014)

43.78+59.3 *is sidereal source*

Elaboration of anomaly in 43.78+59.3: Long-duration (≥ 19 months) radio transient in M82 starburst

Notable theories for 43.78+59.3: Radio outburst of microquasar; radio supernova (disfavored by Gendre et al. 2013, because of persistence); radio transient from supermassive black hole

Anomaly class for 43.78+59.3: 0/IV – Not identified as of yet (IV), but there is a plausible explanation as a microquasar (0)

Notes on anomalous 43.78+59.3: If it is a microquasar, limits on the X-ray luminosity suggest that it is analogous to SS 433 rather than a more typical one (Joseph et al. 2011); previous unknown radio transients have been observed, although not as persistent (Muxlow et al. 2010); similar source in M81 (Anderson et al. 2019a)

References for this anomaly in 43.78+59.3: Muxlow et al. (2010); Joseph et al. (2011); Gendre et al. (2013)

Relationships between 43.78+59.3 and other Exotica Catalog objects: Within the sky region occupied by: M82 [428]; Adjacent on sky to (sharing parent object with): M82 X-1 [310], M82 X-2 [312]

FIRST J141918.9+394036 *is sidereal source*

Elaboration of anomaly in FIRST J141918.9+394036: Decade timescale $\sim$ 1.4 GHz radio transient

Notable theories for FIRST J141918.9+394036: Off-axis gamma-ray burst afterglow

Anomaly class for FIRST J141918.9+394036: 0/IV – Radio transient not obviously associated with known phenomenon (IV), but characteristics explainable as GRB afterglow (0)

Notes on anomalous FIRST J141918.9+394036: Detected in FIRST (1.4 GHz) image with the VLA in 1993, flux: $\sim$ 26 mJy; additional archival data reveal fading to $\sim$ 1 mJy at 1.4 GHz over twenty years (Law et al. 2018); VLBI observations in 2018 reveal 0.62 ± 0.02 Jy (1.6 GHz) source, angular size indicates expansion at $0.1c$ (Marcote et al. 2019); host galaxy: SDSS J141918.81+394035.8

References for this anomaly in FIRST J141918.9+394036: Law et al. (2018); Marcote et al. (2019)

RT 19920826 *is sidereal source*

Elaboration of anomaly in RT 19920826: Long duration (single-epoch) 5 GHz radio transient

Notes on anomalous RT 19920826: Detected in single epoch ($\sim$ 20 min) VLA images of "blank" field, was not detected 56 days later during next epoch; flux: 642 ± 101 mJy (Bower et al. 2007), 460 ± 80 mJy (Frail et al. 2012); of the transients reported in Bower et al. (2007), this was the only one to survive the reliability checks in Frail et al. (2012)

References for this anomaly in RT 19920826: Bower et al. (2007); Frail et al. (2012)

Radio burster: GCRT J1745-3009 [748]

GCRT J1745-3009 *is sidereal source*

Elaboration of anomaly in GCRT J1745-3009: Unknown object in inner Galaxy that emitted five $>$ 1 Jy radio (330 MHz) bursts ($\sim$ 2–10 min duration) with a periodicity of $\sim$ 77 min

Notable theories for GCRT J1745-3009: Unusual type of radio flare from dwarf star or brown dwarf, with 77 min due to rotation; pulsar

Anomaly class for GCRT J1745-3009: IV – Unknown progenitor, although mechanism is probably coherent emission; flaring star is possible but only hypothetical

Notes on anomalous GCRT J1745-3009: Radio bursts detected in 2002 with Very Large Array, no signs of activity in images from 1996, 1998, 2003; bursts rose more slowly than they faded (Hyman et al. 2005); circularly polarizaed bursts detected at 325 MHz in 2003 by Giant Metrewave Radio Telescope (Roy et al. 2010); short ($\sim$ 2 min), fainter (0.05 Jy) burst detected in 2004 by GMRT, with extremely steep spectrum (Hyman et al. 2007); no evident counterpart star found in infrared (Kaplan et al. 2008)

References for this anomaly in GCRT J1745-3009: Hyman et al. (2005); Kaplan et al. (2008); Roy et al. (2010)

Relationship to SETI: GCRT J1745-3009 considered as a hypothetical (though unlikely) ETI beacon in Benford et al. (2010)

Non-repeating fast radio burst: FRB 190523 [749]

Description of anomaly: Unexplained millisecond-duration single radio transient

Notes on anomaly: The prototypical FRB, the Lorimer et al. (2007) burst (FRB 010724), has not been observed to repeat, but its position is not well-determined. Because of speculation that there is more than one population of FRBs (Palaniswamy et al. 2018; Bannister et al. 2019), the separate entries for FRBs are retained in this version of the catalog. It is speculated that all FRBs are repeating; Kumar et al. (2019) discovered very faint FRBs from FRB 171019, which was previously thought to be non-repeating.

Notable theories for anomaly: Many (Platts et al. 2019); low star-formation rate of hosts harder to reconcile with magnetar origin

References for anomaly: Lorimer et al. (2007); Petroff et al. (2019); Cordes & Chatterjee (2019)

Anomaly class: IV – Until recently, no FRBs had an association and thus the progenitor was completely unknown (IV). At least some seem related to magnetars (SGR 1935+2154), but it is more difficult to explain those with hosts deficient in star-formation like FRB 190523.

FRB 190523 *is sidereal source*

Notes on anomalous FRB 190523: Host galaxy confidently identified – redshift: 0.660, stellar mass: $10^{11.07}$ $M_{\odot}$, star formation

rate: $< 1.3\ \mathrm{M_\odot\ yr^{-1}}$ (Ravi et al. 2019)
References for this anomaly in FRB 190523: Ravi et al. (2019)

Relationship to SETI: FRBs have been proposed to be the technosignatures of beamed microwave power (Lingam & Loeb 2017b)

Repeating fast radio burst: FRB 121102 [733]

Description of anomaly: Unknown source of recurring luminous millisecond-duration radio transients, where recurrence is irregular
Notes on anomaly: Because of speculation that there is more than one population of FRBs (Palaniswamy et al. 2018; Bannister et al. 2019), the separate entries for FRBs are retained in this version of the catalog. It is speculated that all FRBs are repeating; Kumar et al. (2019) discovered very faint FRBs from FRB 171019, which was previously thought to be non-repeating
Notable theories for anomaly: Many (Platts et al. 2019), but magnetars (e.g., Popov & Postnov 2010; Beloborodov 2017; Dai & Zhong 2020) are likely responsible for at least some of them, given that SGR 1935+2154 emitted an FRB
References for anomaly: CHIME/FRB Collaboration et al. (2019a); Petroff et al. (2019); Cordes & Chatterjee (2019); CHIME/FRB Collaboration et al. (2019b)
Anomaly class: IV/III – Until recently, no FRBs had an association and thus the progenitor was completely unknown (IV), although if related to the FRB observed from SGR 1935+2154, the mystery is the mechanism rather than the class of objects responsible (III)

FRB 121102 *is sidereal source*
Notes on anomalous FRB 121102: First known repeating FRB and first with a confident host galaxy; located within a star-formation region in a star-forming dwarf galaxy, which favors a progenitor associated with young/massive stars (including magnetars) (Tendulkar et al. 2017; Bassa et al. 2017b); the FRB is associated with an unexplained variable but persistent radio source (Chatterjee et al. 2017)
References for this anomaly in FRB 121102: Spitler et al. (2016); Chatterjee et al. (2017); Tendulkar et al. (2017); Bassa et al. (2017b)
Other references for FRB 121102: Margalit & Metzger (2018); Chatterjee et al. (2017)

Relationship to SETI: Observed by Breakthrough Listen (Gajjar et al. 2018); FRBs have been proposed to be the technosignatures of beamed microwave power (Lingam & Loeb 2017b)

Periodic fast radio burst: FRB 180916.J0158+65 [750]

FRB 180916.J0158+65 *is sidereal source*
Elaboration of anomaly in FRB 180916.J0158+65: Unknown source of recurring luminous millisecond-duration radio transients, where recurrence is periodic
Notable theories for FRB 180916.J0158+65: Many theories for FRBs (Platts et al. 2019); collisions of magnetar with asteroids during periodic passages through debris belt (Dai & Zhong 2020)
Anomaly class for FRB 180916.J0158+65: IV – Unclear how it is related to repeating FRBs, and might be a new type of source (IV).
Notes on anomalous FRB 180916.J0158+65: Radio bursts have 16.35 ± 0.05 day periodicity (Chime/Frb Collaboration et al. 2020); host is relatively nearby ($z = 0.033$) large spiral galaxy (Marcote et al. 2020); no optical, X-ray, or gamma-ray counterparts have been detected (e.g., Tavani et al. 2020; Andreoni et al. 2020)
References for this anomaly in FRB 180916.J0158+65: Marcote et al. (2020); Chime/Frb Collaboration et al. (2020)

Unidentified near-infrared transient: VVV-WIT-02 [751]

VVV-WIT-02 *is sidereal source*
Elaboration of anomaly in VVV-WIT-02: Object that brightened by 6 mag in K_s band over a year or less and then faded over several years
Notable theories for VVV-WIT-02: Recurrent nova
Anomaly class for VVV-WIT-02: 0/IV – The progenitor is unidentified (IV), although Catelan et al. (2014) says it is “probably a recurrent nova”

Notes on anomalous VVV-WIT-02: This source has very little follow-up in the literature
References for this anomaly in VVV-WIT-02: Dekany et al. (2014)

Unidentified optical transients: OTS 1809+31 [752]; MASTER OT J051515.25+223945.7 [753]; USNO-B1.0 1084-0241525 [754]

Description of anomaly: Events in which an unknown source emits detectable optical light for a limited time and then fades below sensitivity
Notable theories for anomaly: Some may be instrumental artifacts like plate defects, or satellite glints
References for anomaly: Hudec (1993); Rau et al. (2009)
Anomaly class: IV – None of the sources have been identified

OTS 1809+31 *is sidereal source*
OTS 1809+31 also known as: Hudec's Object, OT 1946
Elaboration of anomaly in OTS 1809+31: Up to three single-epoch events from 1946–1954, lasting less than about an hour
Notes on anomalous OTS 1809+31: Object is in the field of GRB 790325b, but displaced by 5 ′; no counterparts identified by Ricker et al. (1989), possibly due to proper motion, although Motch et al. (1990) find an unknown UV source at the location; Schaefer et al. (1997) present images of the GRB 790325b field with HST
References for this anomaly in OTS 1809+31: Hudec et al. (1990)

MASTER OT J051515.25+223945.7 *is sidereal source*
Elaboration of anomaly in MASTER OT J051515.25+223945.7: Unknown red optical transient with hour-long variability
References for this anomaly in MASTER OT J051515.25+223945.7: Balanutsa et al. (2015)

USNO-B1.0 1084-0241525 *is sidereal source*
Elaboration of anomaly in USNO-B1.0 1084-0241525: Fading red point source or red transient
Notes on anomalous USNO-B1.0 1084-0241525: Detected in POSS archival images in 1950s; has faded at least 4 mag to 2018.
References for this anomaly in USNO-B1.0 1084-0241525: Villarroel et al. (2016, 2020)
Other references for USNO-B1.0 1084-0241525: Villarroel et al. (2016, 2020)

Pseudo-afterglow: PTF 11agg [755]

PTF 11agg *is sidereal source*
Elaboration of anomaly in PTF 11agg: Fading optical transient caused by extragalactic relativistic explosion
Notable theories for PTF 11agg: Abnormal gamma-ray burst with suppressed or missed high energy emission (Cenko et al. 2013); neutron star merger (Wang & Dai 2013)
Anomaly class for PTF 11agg: 0/II/IV – Could represent a new, unknown phenomenon (IV), but may be explained as a GRB (0), possibly with anomalously low high energy luminosity (II)
Notes on anomalous PTF 11agg: Had an associated radio event, but no detected X-rays or gamma-rays; host galaxy is a dwarf
References for this anomaly in PTF 11agg: Cenko et al. (2013)

Intermediate luminosity red transient: SN 2008S [756]

Anomaly also called: Intermediate luminosity optical transient
Description of anomaly: Months-long eruption of highly-reddened object, brighter than typical nova but fainter than typical supernova
Notes on anomaly: Progenitors have luminosities $\sim (0.5\text{–}1) \times 10^5$ $L_\odot$ (Prieto et al. 2008; Berger et al. 2009) and are surrounded by dust shells with effective temperatures of $\sim$ 300–400 K; radiated energy: $\sim 10^{47}$–10^{48} erg (Smith et al. 2009b; Bond et al. 2009); not to be confused with luminous red novae, which do not have obscured progenitors
Notable theories for anomaly: Electron-capture supernova Prieto et al. (2008); Botticella et al. (2009); luminous blue variable eruption (supernova impostor; Smith et al. (2009b)) or other eruption of massive star (Berger et al. 2009); extreme mass transfer event in binary system (Kashi et al. 2010)
References for anomaly: Thompson et al. (2009)
Anomaly class: IV/III – Although the progenitors appear to be obscured massive stars (perhaps with mass 10–20 $M_\odot$) (III), there is no further consensus about what types of star (IV) or what triggers the events

SN 2008S *is sidereal source*

Notes on anomalous SN 2008S: Host galaxy: NGC 6946
References for this anomaly in SN 2008S: Prieto et al. (2008); Smith et al. (2009b)
Other references for SN 2008S's host: Anand et al. (2018a)
Relationships between SN 2008S and other Exotica Catalog objects: Adjacent on sky to (sharing parent object with): NGC 6946-BH1 [275]
Relationships between SN 2008S and objects in I17: Within the sky region occupied by: NGC 6946

Further examples of anomaly: NGC 300 OT2008-1 (Bond et al. 2009)

Calcium-rich gap transient: PTF 09dav [757]

Anomaly also called: Calcium-strong transients (Shen et al. 2019), calcium-rich supernovae
Description of anomaly: Weeks-long optical transient, brighter than typical nova but fainter than typical supernova with atypically high calcium-to-oxygen ratios
Notes on anomaly: Typically found in early-type galaxies, very far from their host's centers or in intracluster medium (Kasliwal et al. 2012; Lunnan et al. 2017)
Notable theories for anomaly: Mass transfer, merger, or destruction of white dwarfs (Kasliwal et al. 2012; Shen et al. 2019)
References for anomaly: Kasliwal et al. (2012); Frohmaier et al. (2018); Shen et al. (2019)
Anomaly class: IV/III – Progenitors appear to be white dwarfs (III), but no consensus on what type, whether in a binary, or how the events occur (IV)

PTF 09dav *is sidereal source*
References for this anomaly in PTF 09dav: Sullivan et al. (2011); Kasliwal et al. (2012)

Fast blue UV-optical transients: AT 2018cow [758]; Dougie [759]

Description of anomaly: Optical and ultraviolet transients with blue colors that evolve quickly, rising in $\lesssim$ 12 day

AT 2018cow *is sidereal source*
Elaboration of anomaly in AT 2018cow: One of a class of fast blue optical transients found in star-forming galaxies with brightness comparable to supernovae (Drout et al. 2014; Arcavi et al. 2016; Pursiainen et al. 2018); bright eruption with comparable energy release to supernova (5×10^{49} erg), with superlative rise time of 5 day
Notable theories for AT 2018cow: Extremely peculiar supernova or tidal disruption event (Perley et al. 2019; Margutti et al. 2019)
Anomaly class for AT 2018cow: IV – Progenitors and mechanism remain unknown
Notes on anomalous AT 2018cow: Host galaxy: CGCG 137-068, z: 0.014, one of the nearest examples; also detected in X-rays and radio, with self-absorption in the radio spectrum favoring some kind of pre-existing medium surrounding the progenitor (Margutti et al. 2019)
References for this anomaly in AT 2018cow: Drout et al. (2014); Pursiainen et al. (2018); Prentice et al. (2018); Margutti et al. (2019)

Dougie *is sidereal source*
Elaboration of anomaly in Dougie: Extremely bright (up to 5×10^{44} erg s^{-1} optical transient dominated by blue continuum with quick evolution
Notable theories for Dougie: Unusual tidal disruption event; likely distinct from other, fainter fast blue transients (Arcavi et al. 2016)
Anomaly class for Dougie: 0/IV – Source nature and cause of explanation not confirmed (IV), but could be explained as tidal disruption event (0)
Notes on anomalous Dougie: Rise time: 10 day, fell too quickly to be powered by radioisotopes, redshift: 0.191, found near center of host; host galaxy is red
References for this anomaly in Dougie: Vinkó et al. (2015); Arcavi et al. (2016)

Unidentified X-ray transients: XRT 000519 [760]; CDF-S XT1 [761]; CXOU J124839.0-054750 [762]; M86 tULX-1 [763]

Description of anomaly: Events in which an unknown source emits X-rays for a limited time and then fades below sensitivity
Anomaly class: IV – Progenitor and mechanism of these events unknown

XRT 000519 *is sidereal source*
Elaboration of anomaly in XRT 000519: Unexplained soft (1.5 keV) X-ray flash lasting $\sim$ 1 min followed by slow fading of residual X-ray emission over days
Notes on anomalous XRT 000519: Host galaxy probably M86 in the Virgo Cluster (in I17), peak luminosity: 6×10^{42} erg s^{-1}
References for this anomaly in XRT 000519: Jonker et al. (2013)
Other references for XRT 000519's host: Tully et al. (2013)
Relationships between XRT 000519 and other Exotica Catalog objects: Within the sky region occupied by: Virgo Cluster [506]; Adjacent on sky to (sharing parent object with): M86 tULX-1 [763]
Relationships between XRT 000519 and objects in I17: Within the sky region occupied by: M86

CDF-S XT1 *is sidereal source*
Elaboration of anomaly in CDF-S XT1: Unexplained distant X-ray transient with rise time of $\sim$ 1 min and power-law decay (after plateau in related CDF-S XT2)
Notable theories for CDF-S XT1: Millisecond magnetar central engine resulting from neutron star-neutron star merger (Xue et al. 2019; Sun et al. 2019); white dwarf tidal disruption (Peng et al. 2019)
Anomaly class for CDF-S XT1: 0/IV – Possible explanation with the NS-NS merger magnetar model
Notes on anomalous CDF-S XT1: Peak luminosity: $\sim 10^{45}$ erg s^{-1}, unknown redshift; CDF-S XT2 announced in Xue et al. (2019)
References for this anomaly in CDF-S XT1: Bauer et al. (2017)

CXOU J124839.0-054750 *is sidereal source*
Elaboration of anomaly in CXOU J124839.0-054750: Unidentified X-ray source with ultraluminous ($\sim$ (5–6) $\times 10^{39}$ erg s^{-1}) recurrent flares, with flare lasting $\sim$ 1 min
Notable theories for CXOU J124839.0-054750: Recurrent tidal stripping of white dwarf in orbit around black hole (Shen 2019)
Notes on anomalous CXOU J124839.0-054750: Irwin et al. (2016) found two more examples; all are in early-type galaxies; host galaxy: NGC 4697
References for this anomaly in CXOU J124839.0-054750: Sivakoff et al. (2005)
Other references for CXOU J124839.0-054750's host: Tully et al. (2013)

M86 tULX-1 *is sidereal source*
Elaboration of anomaly in M86 tULX-1: Years-long ultraluminous X-ray transient
Notable theories for M86 tULX-1: Black hole X-ray binary
Anomaly class for M86 tULX-1: 0/II/IV – May be explained with black hole accretor (0), although it would be unusually variable (II)
Notes on anomalous M86 tULX-1: Faded from 5×10^{39} erg s^{-1} in 2013 to $\lesssim 10^{38}$ erg s^{-1} in 2016.
References for this anomaly in M86 tULX-1: van Haaften et al. (2019)
Other references for M86 tULX-1's host: Tully et al. (2013)
Relationships between M86 tULX-1 and other Exotica Catalog objects: Within the sky region occupied by: Virgo Cluster [506]; Adjacent on sky to (sharing parent object with): XRT 000519 [760]
Relationships between M86 tULX-1 and objects in I17: Within the sky region occupied by: M86

Unidentified gamma-ray transient: Swift J195509.6+261406 [764]

Swift J195509.6+261406 *is sidereal source*
Swift J195509.6+261406 also known as: GRB 070610
Elaboration of anomaly in Swift J195509.6+261406: Galactic transient superficially appearing like long gamma-ray burst, accompanied by rapid ($<$ 1 s) optical flaring
Notable theories for Swift J195509.6+261406: Black hole X-ray nova (Kasliwal et al. 2008); magnetar (Stefanescu et al. 2008; Castro-Tirado et al. 2008); neutron star X-ray binary (Rea et al. 2011)
Anomaly class for Swift J195509.6+261406: IV – No consensus on nature or mechanism of event, although theories exist
References for this anomaly in Swift J195509.6+261406: Kasliwal et al. (2008); Stefanescu et al. (2008); Castro-Tirado et al. (2008)

Neutrino coincidence: IceCube neutrino multiplet [765]

IceCube neutrino multiplet *is sidereal source*
Elaboration of anomaly in IceCube neutrino multiplet: Near-simultaneous detection of three TeV neutrinos from similar directions
Notable theories for IceCube neutrino multiplet: Suspected to be fluke in atmospheric neutrino background
Anomaly class for IceCube neutrino multiplet: 0/IV – A neutrino transient could represent a new, unknown type of object (IV), but it is more likely to be noise (0)
Notes on anomalous IceCube neutrino multiplet: Neutrinos arrived over 88 s time period
References for this anomaly in IceCube neutrino multiplet: Icecube Collaboration et al. (2017)

3.5 Class V

Impossible eclipsing triple star: KIC 2856960 [766]

KIC 2856960 *is sidereal source*
Elaboration of anomaly in KIC 2856960: Apparent eclipsing triple stellar system for which the geometrical constraints on stellar sizes are in conflict with Kepler's Laws
Notable theories for KIC 2856960: Quadruple star models might explain the light curve without violating Kepler's Laws, but these models need to be extremely fine-tuned
Anomaly class for KIC 2856960: 0/V – The photometry appears to force a violation of Kepler's Laws (and presumably Newtonian gravity), at least in the triple models (V); models with more components may alleviate this problem (0), although they may be contrived
Notes on anomalous KIC 2856960: The relative sizes of the stars also seems anomalous, as both star 1 and star 2 are dwarfs of comparable mass, yet star 2 has a much smaller radius
References for this anomaly in KIC 2856960: Marsh et al. (2014a); Wright et al. (2016)

Relationship to SETI: KIC 2856960 briefly discussed in Wright et al. (2016) as a possible but unlikely technosignature

ANITA upwards showers: AAE-061228 [767]; AAE-141220 [768]; AAC-150108 [769]

Description of anomaly: Particle showers detected in radio by the ANtarctic Impulsive Transient Antenna (ANITA), for which the initiating particle was apparently an EeV energy neutrino propagating through the Earth, as determined from the fact that they develop upwards; the Earth should be opaque to neutrinos at PeV energies and above
Notes on anomaly: If the initiating particles are simply normal neutrinos with EeV energy, then this anomaly actually has nothing to do with the sources, but arises from their interaction with the Earth itself. Nonetheless, the sources of the neutrinos would be unidentified and would be classified as Class IV anomalies. If the particles are not neutrinos but beyond the Standard Model (e.g., Fox et al. 2018), however, then the sources (or the sightlines towards them) do indeed work through new physics
Notable theories for anomaly: Radio frequency interference masquerading as particle showers
Anomaly class: V – Events defy Standard Model of particle physics

AAE-061228 *is sidereal source*
References for this anomaly in AAE-061228: Gorham et al. (2018)

AAE-141220 *is sidereal source*
References for this anomaly in AAE-141220: Gorham et al. (2018)

AAC-150108 *is sidereal source*
References for this anomaly in AAC-150108: Aartsen et al. (2020)

4. Anomalies (SETI)

4.1 Class II

4.1.1 Infrared-excess stars

Mid-infrared–bright stars: IRAS 16406-1406 [770]; IRAS 20331+4024 [771]; IRAS 20369+5131 [772]

Description of anomaly: Three targets whose infrared spectra best match a blackbody spectrum, indicating stars surrounded by opaque material as in a Dyson sphere

Program that detected anomaly: Carrigan (2009) (Dyson sphere search)
References for anomaly: Carrigan (2009)
Anomaly class: II/III – Infrared emission is higher than expected (II), also seems to have blackbody-like spectrum (III)

IRAS 16406-1406 *is sidereal source*

IRAS 20331+4024 *is sidereal source*

IRAS 20369+5131 *is sidereal source*
Notes on anomalous IRAS 20369+5131: Closest match to a blackbody spectrum; distance unknown

Mid-infrared–bright star cluster: IRAS 04287+6444 [773]

IRAS 04287+6444 *is sidereal source*
Elaboration of anomaly in IRAS 04287+6444: Association of mid-infrared sources lacking optical counterparts, suggesting cluster of stars surrounded by opaque material
Notable theories for IRAS 04287+6444: Cluster of young stellar objects still embedded in dusty cloud; cluster of distant starburst galaxies
Anomaly class for IRAS 04287+6444: 0/II – High infrared-to-optical luminositites would be anomalous (II), but Griffith et al. (2015) favors young star cluster
Program that detected IRAS 04287+6444 as anomaly: Ĝ(Griffith et al. 2015; search for Kardashev Type III ETIs in form of galaxies where population veiled by Dyson spheres)
References for this anomaly in IRAS 04287+6444: Griffith et al. (2015)

Microwave-excess star: UW CMi [774]

UW CMi *is sidereal source*
Elaboration of anomaly in UW CMi: Star that appears to have excess microwave emission, suggestive of very cold Dyson sphere
Notable theories for UW CMi: Knot in nearby Galactic dust cloud; circumstellar obscuration
Anomaly class for UW CMi: 0/II – Anomaly is excess in microwave emission (II), but could be explained as result of interstellar dust or circumstellar dust (0)
Program that detected UW CMi as anomaly: Lacki (2016) (search for blackboxes, galaxies shrouded by technological artifacts); uses photometry from *Planck* CSSC2 (Planck Collaboration et al. 2016)
Notes on anomalous UW CMi: Spectrum inconsistent with Rayleigh-Jones tail of excess blackbody emission; UW CMi is a Mira-type variable and might be expected to have obscuration
References for this anomaly in UW CMi: Lacki (2016)

4.1.2 Infrared-excess galaxies

Mid-infrared–bright galaxy: WISE J224436.12+372533.6 [775]

WISE J224436.12+372533.6 *is sidereal source*
Elaboration of anomaly in WISE J224436.12+372533.6: Galaxy with mid-infrared excess emission, suggestive of stellar population surrounded by opaque material like Dyson spheres
Anomaly class for WISE J224436.12+372533.6: II – Defined by excess quantities of mid-infrared emission
Program that detected WISE J224436.12+372533.6 as anomaly: Ĝ(Griffith et al. 2015; search for Kardashev Type III ETIs in form of galaxies where population veiled by Dyson spheres)
References for this anomaly in WISE J224436.12+372533.6: Griffith et al. (2015)

Mid-infrared–radio correlation outliers: UGC 3097 [776]; NGC 814 [777]; ESO 400-28 [778]; MCG+02-60-017 [779]

Description of anomaly: Galaxies that have excess infrared emission relative to that predicted from radio emission, using the infrared–radio correlation that holds for star-forming galaxies
Notes on anomaly: Listed as Seyfert in Simbad.
Notable theories for anomaly: Extremely young starbursts where supernovae have not accelerated cosmic ray electrons and radio emission has not yet begun; dust-obscured radio quiet AGN
Program that detected anomaly: Garrett (2015) (search for Kardashev Type III ETIs in form of galaxies where population veiled

by Dyson spheres)
References for anomaly: Garrett (2015)
Anomaly class: II – Defined by excess quantities of mid-infrared emission

UGC 3097 *is sidereal source*

NGC 814 *is sidereal source*

ESO 400-28 *is sidereal source*

MCG+02-60-017 *is sidereal source*

4.1.3 Optically faint objects

Abnormally faint star: TYC 6111-1162-1 [780]

Description of anomaly: Star that is underluminous for its spectral type, as determined by *Gaia*, suggestive that star is partially obscured by opaque material like partial Dyson spheres
Notable theories for anomaly: Incorrect distance leads to luminosity underestimation, due to being in a binary with a white dwarf
Program that detected anomaly: Zackrisson et al. (2018) (search for partial Dyson spheres by luminosity–spectral type discrepancies)
References for anomaly: Zackrisson et al. (2018)
Anomaly class: 0/II – Optical luminosity is anomalously low quantity (II), but possible explanation suggested (0)

TYC 6111-1162-1 *is sidereal source*

Underluminous galaxy: UGC 5394 [781]; NGC 4502 [782]; NGC 4698 [783]; IC 3877 [784]; AGC 470027 [785]

Description of anomaly: Disk galaxies that are outliers from Tully-Fisher relation between optical luminosity and rotation speed; these are underluminous, suggesting that stellar population is obscured by opaque material like Dyson spheres
Notes on anomaly: These galaxies are all classed as grade A in quality, meaning that they lie in groups with relatively well-determined distances, reducing the chance that the apparent underluminosity is the result of an underestimated distance. None have the mid-infrared excess expected from waste heat from obscuration by classical Dyson spheres, leading Zackrisson et al. (2015) to conclude they are mundane.
Notable theories for anomaly: Incorrect distance leads to luminosity underestimation
Program that detected anomaly: Zackrisson et al. (2015) (search for Kardashev Type III ETIs in form of galaxies where population veiled by Dyson spheres)
References for anomaly: Zackrisson et al. (2015)
Anomaly class: II – Optical luminosity is anomalously low quantity (II)

UGC 5394 *is sidereal source*

NGC 4502 *is sidereal source*
Relationships between NGC 4502 and other Exotica Catalog objects: Within the sky region occupied by: Virgo Cluster [506]

NGC 4698 *is sidereal source*
Relationships between NGC 4698 and other Exotica Catalog objects: Within the sky region occupied by: Virgo Cluster [506]

IC 3877 *is sidereal source*

AGC 470027 *is sidereal source*

4.2 Class III

4.2.1 Narrowband radio emitting stars

Narrowband radio stars: HR 6171 [786]; GJ 1019 [787]; GJ 299 [788]; LHS 1140 [088]; TRAPPIST-1 [091]

Description of anomaly: Stars from which narrowband radio signals, a classical technosignature of a radio beacon, have been detected by a SETI program
Anomaly class: III – Narrowband radio emission of this sort would be sign of a qualitatively new phenomenon in or around these stars

HR 6171 *is sidereal source*

Program that detected HR 6171 as anomaly: Blair et al. (1992) (search for narrowband radio beacons around stars and globular clusters at 4.46 GHz = $\pi \times 1.42$ GHz magic frequency; 0.6 Hz frequency resolution)
Notes on anomalous HR 6171: Weak signal lasting for several hours detected in one epoch (1990); significance low
References for this anomaly in HR 6171: Blair et al. (1992)
HR 6171 in I17

GJ 1019 *is sidereal source*
Program that detected GJ 1019 as anomaly: SERENDIP III (Bowyer et al. 2016; commensal search for narrowband radio emission at 70 cm ≡ 430 MHz)
Notes on anomalous GJ 1019: Highest score using “algorithm 1”; detected in two of six observations
References for this anomaly in GJ 1019: Bowyer et al. (2016)
Other references for GJ 1019: Sandage (1997)

GJ 299 *is sidereal source*
Program that detected GJ 299 as anomaly: SERENDIP III (Bowyer et al. 2016; commensal search for narrowband radio emission at 70 cm ≡ 430 MHz)
Notes on anomalous GJ 299: Highest score of candidates with associated stars using “algorithm 3”; only one observation made
References for this anomaly in GJ 299: Bowyer et al. (2016)

LHS 1140 *is sidereal source*
Notable theories for LHS 1140: Radio frequency interference, observed at very nearby frequency
Anomaly class for LHS 1140: 0/III – Radio frequency interference is plausible explanation for sources (0)
Program that detected LHS 1140 as anomaly: Pinchuk et al. (2019) (search for narrowband radio beacons around stars in L-band, 1.15–1.73 GHz)
References for this anomaly in LHS 1140: Pinchuk et al. (2019)
Other references for LHS 1140: Dittmann et al. (2017); Ment et al. (2019)

TRAPPIST-1 *is sidereal source*
Notable theories for TRAPPIST-1: Radio frequency interference, observed at very nearby frequency
Anomaly class for TRAPPIST-1: 0/III – Radio frequency interference is plausible explanation for sources (0)
Program that detected TRAPPIST-1 as anomaly: Pinchuk et al. (2019) (search for narrowband radio beacons around stars in L-band, 1.15–1.73 GHz)
References for this anomaly in TRAPPIST-1: Pinchuk et al. (2019)
Other references for TRAPPIST-1: Gillon et al. (2017); Gonzales et al. (2019); Luger et al. (2017)

4.2.2 Stars with anomalous optical emission

Optical pulse star: HD 220077 [789]; HIP 107359 [790]

Description of anomaly: Stars from which candidate nanosecond-duration optical transients were detected
Notable theories for anomaly: Statistical fluctuations in background noise in detector
Program that detected anomaly: Harvard OSETI (Howard et al. 2004; search for nanosecond optical pulses)
References for anomaly: Howard et al. (2004)
Anomaly class: 0/III – Optical nanosecond pulsations would be an unprecedented phenomenon (III), but noise is a viable explanation for the candidates (0)

HD 220077 *is sidereal source*
Notes on anomalous HD 220077: Three apparent pulses detected in ten minutes; considered by Howard et al. (2004) to be most interesting candidate

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HIP 107359 *is sidereal source*
Notes on anomalous HIP 107359: Only joint trigger between Princeton and Harvard

Coherently variable star: TYC 3010-1024-1 [791]

Description of anomaly: Stars with claimed coherent picosecond optical variability, as inferred from spectral features in archival data
Notes on anomaly: Borra & Trottier (2016) identified 234 candidate stars, and noted they were F2–K1 dwarfs, which might

be expected for planetbound ETIs; Isaacson et al. (2019) did not confirm signal in re-observations of three bright stars from sample
Notable theories for anomaly: Instrumental artifact; false positive from natural stellar lines (Hippke 2019)
Program that detected anomaly: Borra & Trottier (2016) (search for coherent picosecond optical variability)
References for anomaly: Borra & Trottier (2016)
Anomaly class: 0/III – Variability of this sort has never been observed in an AGN before, and it would be a new phenomenon; but plausible explanation as instrumental or natural effect exist

TYC 3010-1024-1 *is sidereal source*
Notes on anomalous TYC 3010-1024-1: Brightest star of the candidates in Borra & Trottier (2016)

4.3 Class IV

4.3.1 Unidentified narrowband radio sources

Narrowband radio transient: Wow! Signal (A) [792]; Wow! Signal (B) [793]

Wow! Signal (A) *is sidereal source*
Elaboration of anomaly in Wow! Signal (A): Bright (60 Jy), narrowband (< 10 kHz) radio signal with duration ~ 1 min
Notable theories for Wow! Signal (A): Radio frequency interference
Anomaly class for Wow! Signal (A): IV – If real, narrowband radio emission of this sort would represent a new phenomenon
Program that detected Wow! Signal (A) as anomaly: Big Ear (survey of much of sky for narrowband radio technosignatures at 1.420 GHz)
Notes on anomalous Wow! Signal (A): The Big Ear used two radio beams that swept over sky regions in succession, one trailing the other by three minutes; since the Wow! signal was only detected in one beam but not the other, and since which beam the detection occured in wasn't recorded, there are two possible positions on the sky it could have originated. Observations by Gray & Marvel (2001); Gray & Ellingsen (2002) of the sky regions have not found any source, even down to much deeper sensitivity.
References for this anomaly in Wow! Signal (A): Dixon (1985); Gray (2012)
Relationships between Wow! Signal (A) and other Exotica Catalog objects: Alternate localization of: Wow! Signal (B) [793]

Wow! Signal (B) *is sidereal source*
References for this anomaly in Wow! Signal (B): Dixon (1985); Gray (2012)
Relationships between Wow! Signal (B) and other Exotica Catalog objects: Alternate localization of: Wow! Signal (A) [792]

Ultranarrowband radio emission: 5.13h +2.1 [794]; 08.00h -08.50 [795]; 03.10h +58.0 [796]; 11.03.91 [797]

Description of anomaly: Ultranarrowband radio sources detected with no associated counterparts
Anomaly class: IV – If real, ultranarrowband radio emission would represent a new phenomenon

5.13h +2.1 *is sidereal source*
Program that detected 5.13h +2.1 as anomaly: SERENDIP III (Bowyer et al. 2016; commensal search for narrowband radio emission at 70 cm $\equiv$ 430 MHz; 0.6 Hz frequency resolution)
Notes on anomalous 5.13h +2.1: Highest score using "algorithm 2"; detected in two of four observations
References for this anomaly in 5.13h +2.1: Bowyer et al. (2016)

08.00h -08.50 *is sidereal source*
Program that detected 08.00h -08.50 as anomaly: META (Horowitz & Sagan 1993; survey of entire sky for ultranarrowband radio technosignatures at 1.420 GHz and 2.840 GHz; 0.05 Hz frequency resolution)
Notes on anomalous 08.00h -08.50: By far the strongest detection in META with $S/N = 747$, detected at 2.84 GHz
References for this anomaly in 08.00h -08.50: Horowitz & Sagan (1993)

03.10h +58.0 *is sidereal source*
Program that detected 03.10h +58.0 as anomaly: META (Horowitz & Sagan 1993; survey of entire sky for ultranarrowband radio technosignatures at 1.420 GHz and 2.840 GHz; 0.05 Hz frequency resolution)
Notes on anomalous 03.10h +58.0: By far the strongest 1.42 GHz detection with $S/N = 224$
References for this anomaly in 03.10h +58.0: Horowitz & Sagan (1993)

11.03.91 *is sidereal source*
Program that detected 11.03.91 as anomaly: META II (Colomb et al. 1995; survey of southern sky for ultranarrowband radio

technosignatures at 1.420 GHz; 0.05 Hz frequency resolution)
Notes on anomalous 11.03.91: Greatest P_0 (intensity relative to background) of candidates, although only barely above threshold
References for this anomaly in 11.03.91: Colomb et al. (1995)

4.3.2 Unidentified infrared sources

Unidentified mid-infrared candidate galaxies: WISE 0735-5946 [798]; IRAS 16329+8252 [799]

Description of anomaly: Mid-infrared sources, probably galaxies, consistent with waste heat from Kardashev Type III ETI
Notes on anomaly: These sources are noted to be essentially unstudied in literature by Griffith et al. (2015)
Program that detected anomaly: Ĝ(Griffith et al. 2015; search for Kardashev Type III ETIs in form of galaxies where population veiled by Dyson spheres)
References for anomaly: Griffith et al. (2015)
Anomaly class: IV – Nature of objects unknown

WISE 0735-5946 *is sidereal source*
Notes on anomalous WISE 0735-5946: Possible redshifted spectral line

IRAS 16329+8252 *is sidereal source*
Notes on anomalous IRAS 16329+8252: Appears to have two subcomponents connected by optical bridge, suggestive of merging galaxies

4.3.3 Unidentified optical sources

Vanishing star-like source: USNO-B1.0 1084-0241525 [754]

USNO-B1.0 1084-0241525 *is sidereal source*
Elaboration of anomaly in USNO-B1.0 1084-0241525: Fading red point source or red transient, suggestive of star being hidden by megastructure construction
Anomaly class for USNO-B1.0 1084-0241525: IV – Source nature unknown
Program that detected USNO-B1.0 1084-0241525 as anomaly: Villarroel et al. (2016) (search for disappearing stars, which could be due a sign of megastructures)
Notes on anomalous USNO-B1.0 1084-0241525: Detected in POSS archival images in 1950s; has faded at least 4 mag to 2018.
References for this anomaly in USNO-B1.0 1084-0241525: Villarroel et al. (2016, 2020)
Other references for USNO-B1.0 1084-0241525: Villarroel et al. (2016, 2020)

5. Control

CSL-1 [800]

Original observation motivating interest: Pair of very similar galaxies at nearly same redshift
Original explanation of target: Cosmic string acting as gravitational lens produces duplicate images of single galaxy
Anomaly class of original explanation: 0/IV – Cosmic strings would be an entirely new phenomenon with poorly understood physics (IV), although they are predicted by theory (0)
References for original explanation: Sazhin et al. (2003, 2006)
Current explanation of target: Pair of similar but distinct interacting elliptical galaxies
References for target as currently understood: Agol et al. (2006); Sazhin et al. (2007)

CSL-1 *is sidereal source*

GRB 090709A [801]

Original observation motivating interest: Gamma-ray burst with apparent 8 s quasi-periodic oscillations in light curve
Anomaly class of original explanation: III – Quasiperiodic pulsations as apparently observed are not generally associated with gamma-ray burst
References for original explanation: Markwardt et al. (2009); Golenetskii et al. (2009); Gotz et al. (2009)
Current explanation of target: Normal gamma-ray burst had no periodicity; significance overestimated because of non-white "noise" fluctuations in intrinsic GRB light curve
References for target as currently understood: de Luca et al. (2010); Cenko et al. (2010)

GRB 090709A *is sidereal source*

GW100916 (A) [802]; **GW100916 (B)** [803]

Original observation motivating interest: First stellar-mass black hole merger observed in gravitational waves
Anomaly class of original explanation: 0 – Predicted phenomenon explicitly sought by detector
References for original explanation: Evans et al. (2012b)
Current explanation of target: Planned blind injection to test analysis of data
References for target as currently understood: Evans et al. (2012b)
Notes for target: LIGO cannot precisely determine the precise locations of events, but instead gives probability distributions over the sky. The two targets here represent two pointings reported by *Swift* to follow up on the event.

GW100916 (A) *is sidereal source*
Relationships between GW100916 (A) and other Exotica Catalog objects: Alternate localization of: GW100916 (B) [803]

GW100916 (B) *is sidereal source*
Relationships between GW100916 (B) and other Exotica Catalog objects: Alternate localization of: GW100916 (A) [802]

HD 117043 [804]

Original observation motivating interest: Spectrum of star showed strong potassium lines, which had disappeared when spectrum taken next night
Original explanation of target: Potassium line-emitting stellar flares
Anomaly class of original explanation: III – New type of flare phenomenon hosted by stars with unexplained mechanism
References for original explanation: Barbier & Morguleff (1962)
Current explanation of target: Stray light from matches in observatory
References for target as currently understood: Wing et al. (1967)
Notes for target: Wing et al. (1967) was not able to prove that matches were responsible, but the flares were never shown to actually be of stellar origin.

HD 117043 *is sidereal source*
HD 117043 in I17

Hertzsprung's Object [805]

Original observation motivating interest: Bright optical transient, of hour duration or more
Anomaly class of original explanation: IV – Would be unknown type of optical transient
References for original explanation: Hertzsprung (1927); Klemola (1983)
Current explanation of target: False images due to static electric discharge
References for target as currently understood: Schaefer (1983)
Notes for target: The apparent object was found as a double image on a plate exposed twice for 13 and 29.3 min over the course of about an hour, supporting its existence as an actual object. Klemola (1983) notes the profile is nonstellar but suggested it could result from a peculiar spectrum. Schaefer (1983) found similar defects throughout the plate field that are consistent with those produced by electric discharge, implying this object is simply a coincidence between them. The coordinates used in the Catalog come from the Galactic coordinates in Klemola (1983).

Hertzsprung's Object *is sidereal source*
Hertzsprung's Object in I17

HIP 114176 [806]

Original observation motivating interest: Star in the *Hipparcos* catalog
Anomaly class of original explanation: 0 – Typical star
References for original explanation: Perryman et al. (1997)
Current explanation of target: Catalog error due to scatterred light from bright star
References for target as currently understood: Perryman et al. (1997)
Notes for target: Perryman et al. (1997) describes the *Hipparcos* catalog, which contains HIP 114176; it was never specifically discussed. HIP 114176 was found through a search of "Not an object" in Simbad

HIP 114176 *is sidereal source*

KIC 5520878 [807]

Original observation motivating interest: RR Lyrae star with variable oscillation periods; autocorrelation of period lengths is enhanced for periods separated by prime numbers of periods
Original explanation of target: ETI modulation of stellar variability (only a working hypothesis during analysis)
Anomaly class of original explanation: III – Prime number patterns generally not considered to be natural, and possible sign of ETIs
References for original explanation: Hippke et al. (2015)
Current explanation of target: Fluke due to ratio of two distinct variability periods (explained in same paper that discussed potential anomaly)
References for target as currently understood: Hippke et al. (2015)

KIC 5520878 *is sidereal source*

Relationship to SETI: Learned et al. (2008) proposed that ETIs could alter stellar variability with neutrino beams to communicate

KIC 9832227 [808]

Original observation motivating interest: Contact binary with rapidly decreasing period
Original explanation of target: Imminent stellar merger and luminous red nova
Anomaly class of original explanation: 0 – Known phenomenon; notable mainly because the events are rare
References for original explanation: Molnar et al. (2017a)
Current explanation of target: W UMa-type binary in hierarchical triple, in combination with timing typo
References for target as currently understood: Socia et al. (2018); Kovacs et al. (2019)

KIC 9832227 *is sidereal source*

KOI 6705.01 [809]

Original observation motivating interest: *Kepler* star displaying no transits for first two years, then transits of long duration and increasing depth during last two years

Original explanation of target: Variable Moon-sized transiter, possibly a dust cloud (only a working hypothesis during analysis)
Anomaly class of original explanation: III – New type of transit phenomenon not seen in stars
References for original explanation: Gaidos et al. (2016); Coughlin et al. (2016)
Current explanation of target: Detector problem
References for target as currently understood: Gaidos et al. (2016); Coughlin et al. (2016)
Notes for target: Coughlin et al. (2016) describes the data used by Gaidos et al. (2016), but only briefly mentions KOI 6705.01 itself

KOI 6705.01 *is sidereal source*

Perseus Flasher [810]

Original observation motivating interest: Bright ($V = -2$–4), short (1 s) optical flashes; one photographed, others from naked eye
Anomaly class of original explanation: IV – Would have been new, unexplained class of transients
References for original explanation: Katz et al. (1986)
Current explanation of target: Satellite glints or illusory flashes due to physiological response in eyes
References for target as currently understood: Halliday et al. (1987); Corso et al. (1987); Maley (1987); Schaefer et al. (1987); Borovicka & Hudec (1989)
Notes for target: Halliday et al. (1987) reported no flashes during times when they were supposed to occur

Perseus Flasher *is sidereal source*

PSR B1829-10 b [811]

Original observation motivating interest: Unexplained timing residuals from pulsar PSR B1829-10
Original explanation of target: First exoplanet discovered, with mass ~ 12 $M_{\oplus}$ and orbital period 0.5 yr
Anomaly class of original explanation: I/III – Like PSR 1257+12 ABC, the location of the planet – around a pulsar – is anomalous (I), could be interpreted as qualitatively new accessory phenomenon for pulsar itself (III)
References for original explanation: Bailes et al. (1991)
Current explanation of target: Pulsar timing correction error due to neglect of Earth's orbital eccentricity
References for target as currently understood: Lyne & Bailes (1992)

PSR B1829-10 b *is sidereal source*

OT 060420 [812]

Original observation motivating interest: Bright ($V = 5$) optical flash recorded by two CONCAM cameras at different locations simultaneously
Anomaly class of original explanation: IV – Would have been new, unexplained class of transients
References for original explanation: Shamir & Nemiroff (2006)
Current explanation of target: Coincidental cosmic ray hits on both cameras
References for target as currently understood: Shamir & Nemiroff (2006); Smette (2006); Nemiroff & Shamir (2006)
Notes for target: Transient was not simultaneously detected by MASCOT survey (Smette 2006), indicating it was not real

OT 060420 *is sidereal source*

SSSPM J1549-3544 [813]

Original observation motivating interest: Star with high proper motion and featureless spectrum
Original explanation of target: Candidate for nearest white dwarf (4 ± 1 pc)
Anomaly class of original explanation: 0 – Only the possible proximity of the object was significant
References for original explanation: Scholz et al. (2004)
Current explanation of target: Distant (114 pc) high-velocity halo star
References for target as currently understood: Farihi et al. (2005)
Notes for target: Farihi et al. (2005) report the detection of spectral lines, invalidating classification as cool white dwarf

SSSPM J1549-3544 *is sidereal source*

Swift Trigger 954840 [814]

Original observation motivating interest: Increased rate in *Swift*-BAT and possible localized source resulting in trigger
Original explanation of target: Candidate gamma-ray burst
Anomaly class of original explanation: 0 – Would have been unremarkable GRB
References for original explanation: Lipunov et al. (2020); Gropp et al. (2020)
Current explanation of target: Statistical fluctuation
References for target as currently understood: Gropp et al. (2020)
Notes for target: Lipunov et al. (2020) reports optical observations by MASTER-IAC resultant from trigger; no source was found. This trigger was chosen as one of the most recent false alarms at the time of selection.

Swift Trigger 954840 *is sidereal source*

TU Leo [815]

Original observation motivating interest: Newly discovered dwarf nova system
Anomaly class of original explanation: 0 – Would have been unremarkable dwarf nova
References for original explanation: Schmadel et al. (1996)
Current explanation of target: Background star coincident with bright asteroid 8 Flora on discovery plate
References for target as currently understood: Schmadel et al. (1996)

TU Leo *is sidereal source*

VLA J172059.9+385226.6 [816]

Original observation motivating interest: Unknown type of radio transient
Anomaly class of original explanation: IV – Would have been unexplained event
References for original explanation: Ofek et al. (2010)
Current explanation of target: Known radio source, misidentified because of incorrect metadata regarding pointing of VLA
References for target as currently understood: Ofek et al. (2010)
Notes for target: Radio flux apparently only in last ten seconds of integration when metadata inconsistent with actual pointing; resulted in HST and Keck follow-up

VLA J172059.9+385226.6 *is sidereal source*

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