



Breakthrough Listen Stellar Targets: All Sky

Jan 3, 2016

This is a description of the selection process of target stars for the Breakthrough LISTEN (BL) program for the entire sky (“All Sky”) useful for GBT, APF, Parkes, and any other telescopes. The target stars are located at all Declinations, with a uniform selection criteria from the south to north celestial poles, and the stars are composed of two sub-samples:

- All known stars within 5 parsecs (see Section 1, below).
- Main Sequence and Giant stars between 5-50 pc, drawn from the brightest 100 stars within domains along the H-R Diagram having a size of 0.1×2.0 mag in B-V and M_V (see Section 2, below).

1. *The 5-Parsec Sub-sample*

We constructed a target star sample for our “5 Parsec” survey for BL, containing all stars within 5 parsecs. Designed for the GBT, APF, Parkes, and any other telescopes (and NIROSETI, with PI Shelley Wright), this sub-sample will contain **all stars within 5 parsecs and all Declinations**.

To identify all stars within 5 parsecs, we scoured two catalogs, namely the RECONS list online (complete catalog of known nearest stars) and the Gliese Catalog of Nearby Stars (3rd Edition). We included all stars within 5 parsecs and extracted their stellar parameters, notably their coordinates, trigonometric parallax, proper motion and photometry, including V and B-V magnitudes. Nearly all of these stars have large proper motions, in the range 0.1 to 5 arcsec/yr, accumulating during 16 years (since epoch 2000) to tens of arcseconds, comparable to the field of view of optical telescopes. Thus we provide in this current BL Target List a careful advancing due to proper motion of each star’s coordinates to the present epoch, 2016, of ongoing BL observations. Advancing for future epochs of observations will be useful. This is routinely done with the IDL codes, “near_stars.pro” and “advance03.pro” that we make publicly available, as with all BL software and data.

Roughly half of the stars in the 5-parsec sample have a binary companion. For any star having a known companion located within an angular separation of 2 arcsec, we simply entered the star in the BL Target List once, as they will not be spatially resolved at either optical or radio wavelengths. We should avoid pointing the telescope twice at such close binaries.

The H-R Diagram of the 5 parsec star sample is shown in **Figure 1**, in the two parameter domain of star color, B-V, and absolute visual magnitude, M_V . Most of the 5 parsec stars are red, low mass, M dwarfs with $B-V > 1.0$. The BL observing strategy may be structured to boost the exposure time of these nearby stars, to achieve low flux detection thresholds, as described below.

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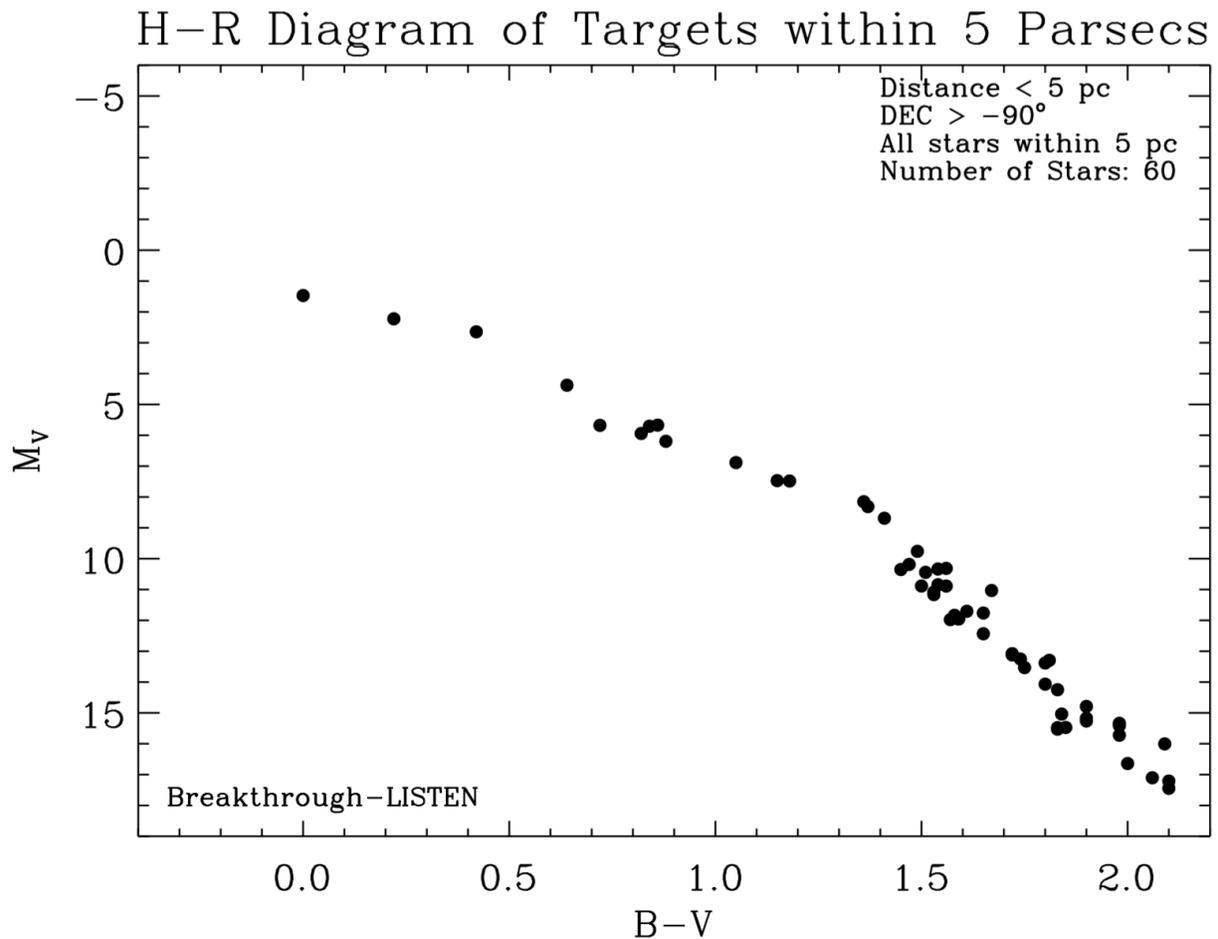


Figure 1. The H-R Diagram of the 5 Parsec sample of target stars for BL. It includes all stars within 5 pc over the entire sky, north and south.

2. The 5-50pc Sub-Sample of Main Sequence and Giant Stars

The second sub-sample of the BL Target List includes nearby main sequence and giant stars at all declinations, north and south, suitable for the Green Bank, APF, Parkes (and any other) telescopes. The criteria for the selection of 5-50 pc target stars follow from the goal of searching nearby stars with a broad sampling of all types of normal stars. The 5-50pc target stars were drawn from the Hipparcos Catalog (providing accurate coordinates, distances, and proper motions) and all located within 50 parsecs (163 light years) and at any declination. The following descriptions and figures illustrate the selection criteria of these 5-50pc main sequence and giant stars.

Figure 2 shows the H-R Diagram of the 5-50 sub-sample of stars. The figure exhibits rectangular domains along the Main Sequence stars in color (B-V) and visible luminosity (M_V) of size 0.1 mag and 2.0 mag, respectively, as shown in the upper left of Figure 2. Many domains contain more than 100 stars in this distance

3. The Entire (Combined) Target sample for Breakthrough LISTEN

We combined the two sub-samples (5 pc and 5-50 pc) to produce the final set of 1709 target stars. The H-R Diagram of that final sample of stars is shown in **Figure 3**. It shows that combining our two sub-samples yielded a broad sampling of stars along the main sequence and in the giant domain. The nearest stars, within 5 pc, are composed mostly of M dwarfs, down to spectral type M8 ($B-V > 2$), near the brown dwarf boundary.

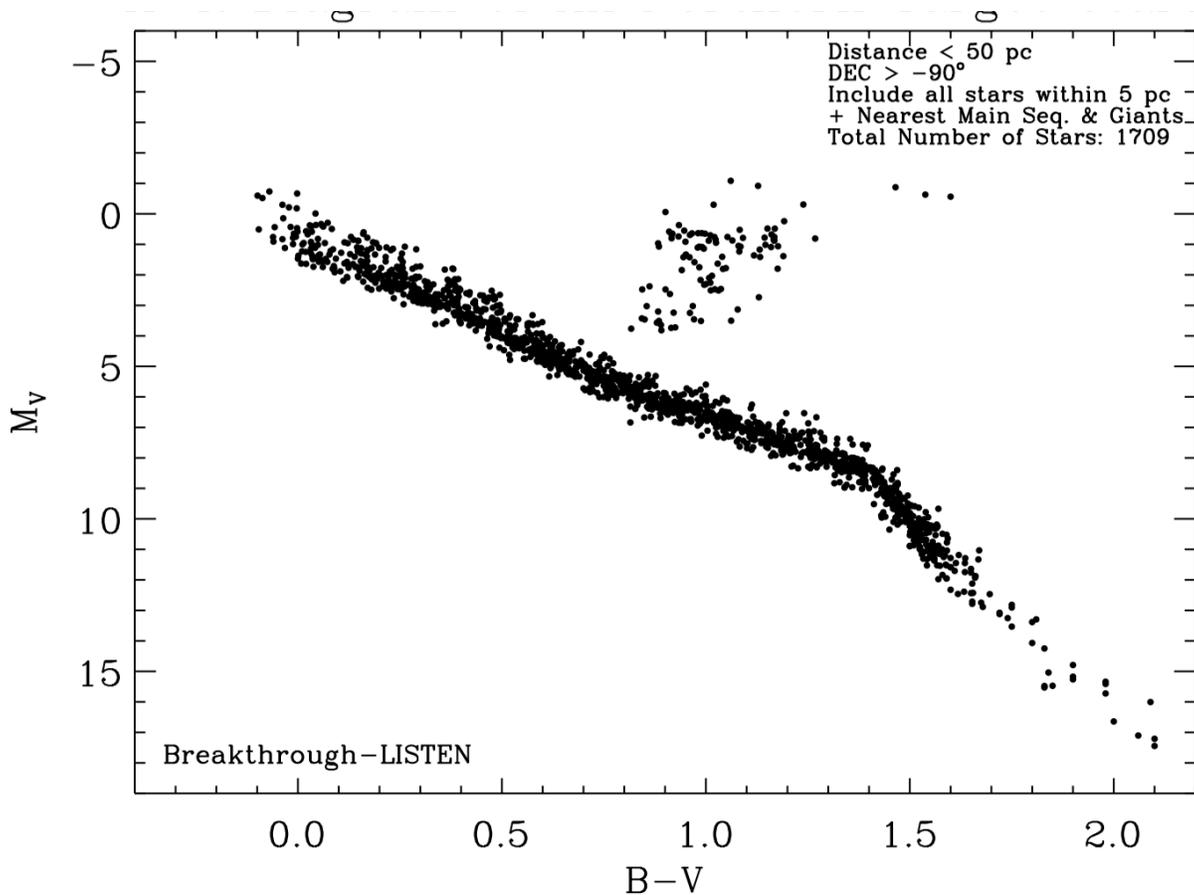


Figure 3. The H-R Diagram of the entire set of Breakthrough LISTEN target stars for the entire sky. It includes all stars within 5 parsecs and the nearest stars within $B-V$ domains in a 5-50 parsec sub-sample. The goal is to construct a sample of target stars for Breakthrough LISTEN that has a sampling of the diversity of stars found within 50 parsecs.

Figure 4 shows the position of all 1,709 targets (Main Sequence and Giant stars) on the sky in Equatorial Coordinates. Each star is color coded to represent its spectral type (BAFGKM), from hottest to coolest surface

temperatures. Sun-like stars (G-type) are shown in yellow.

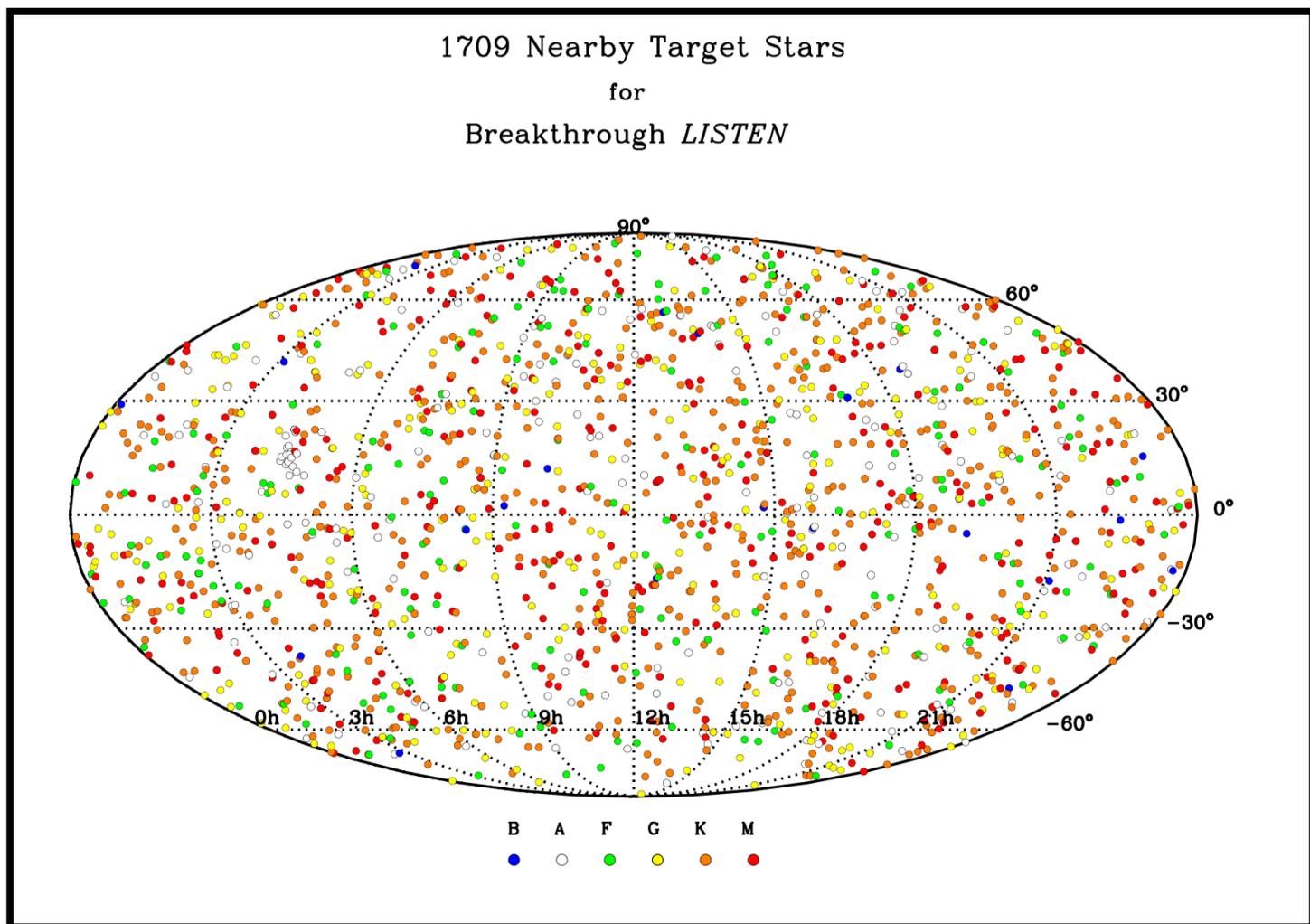


Figure 4. A map, in equatorial coordinates, of the Breakthrough LISTEN target stars for the entire sky. The position of the dots represents the position on the celestial sphere, and the color represents the spectral type, with the code give at bottom. This spatial distribution is nearly uniform over the sky because all of the stars reside within the 50 pc sphere within the disk of the Milky Way Galaxy.

The entire list of 1709 BL target stars is given in a separate text file and CSV file: `BL_star_targets_all_sky.txt` and `BL_star_targets_all_sky.csv`. The columns list star names, coordinates for epoch 2016.0, V magnitude, spectral type, and distance in parsecs. (This list is generated by the IDL code `near_stars.pro`.)

The entire target list contains 1709 stars, comprising a broad collection of nearby target-stars for the Breakthrough LISTEN GBT and APF searches for intelligent life, with suppressed bias against any type of star.

We retained stars with having H-burning ages under a few billion years as well as giants, which evolved off the main sequence less than 100 million years ago. This survey spreads the investment of telescope time across a broad distribution of the nearest main sequence and giant stars, with special inclusion of all stars within 5 pc.

The histogram of distances to the entire target sample of 1709 stars is shown in **Figure 5**. The distances range from 1.3 pc (the Alpha Cen triple system) to 50 pc. The peak is near 25 pc, representing the typical distance to the nearest 100 FGK stars within 50 pc. The M dwarfs are concentrated to distances under 20 pc, due to their high number density in the Galactic disk and to the purposeful inclusion of all stars within 5 pc that are mostly M dwarfs. The most distant stars in the sample, located beyond 30 pc, are composed mostly of early G-, F-, A-, and B-type stars and giants, that have a lower number density for which the nearest are farther away.

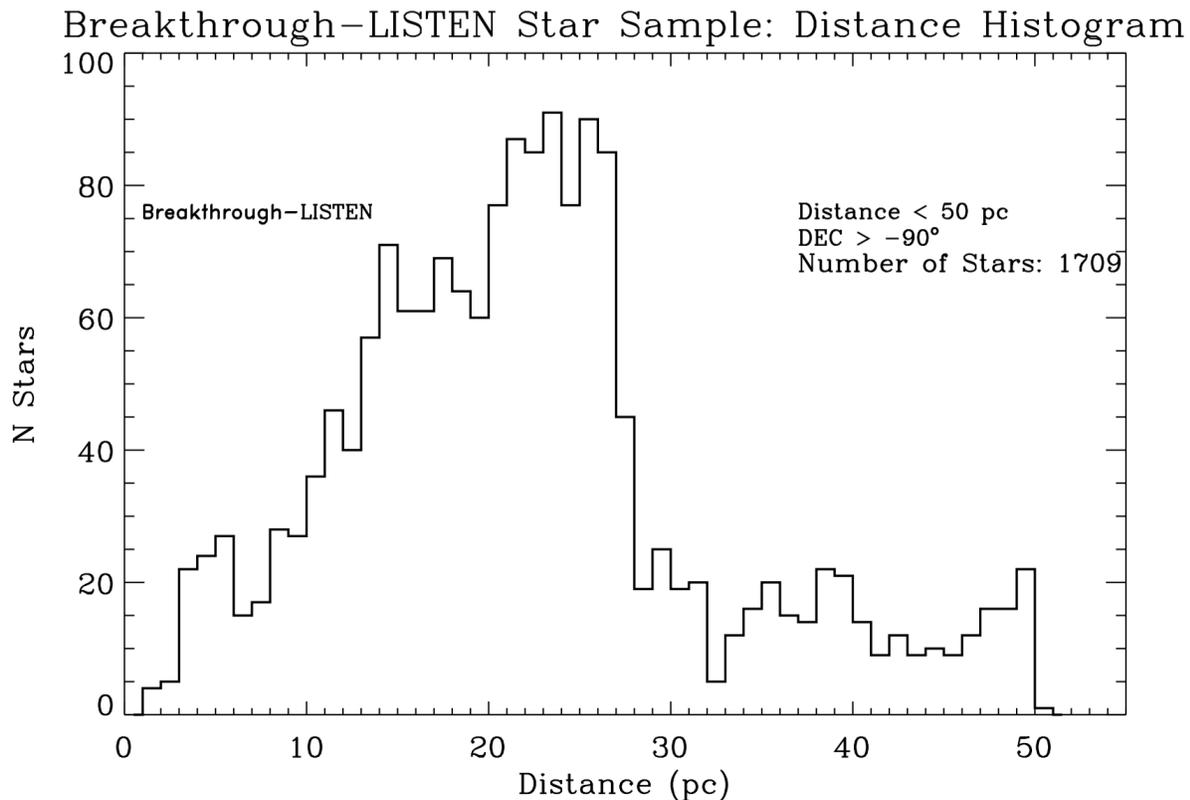


Figure 5. The histogram of distances to all 1709 target stars of the Breakthrough LISTEN survey. The nearest stars (at far left) are typically M dwarfs and the bulk of the stars from 10-30 pc are typically FGKM stars. The stars beyond 30 pc are F, A, and B stars and giants, for which their low number density in the Galaxy necessitates greater distances to include the nearest of them.

4. Integration times for Green Bank Telescope

A question arises about choices for the GBT integration times for the 1709 target stars. There is a desire to achieve a nearly uniform detection threshold for the intrinsic luminosity of any radio source at each star system, with its known distance. We adopt the usual metric, Equivalent Isotropically Radiated Power (EIRP), which is the power the detected source would be emitting, based on its flux at Earth, if the source were emitting isotropically. Obviously, a strictly uniform detection EIRP threshold requires exposure times that are proportional to distance squared. Such an exposure policy has the advantage that it yields a quantified, uniform intrinsic threshold for all stars in the survey, overcoming the diverse flux dilutions caused by the various distances to each star system.

The downside of such a uniform EIRP threshold is that the stars at distances of, say, 50 pc and 5 pc will receive a factor of 100 different amounts of telescope time. The nearest stars (at 5 pc) would receive less than 1% of the telescope allotment of the distant stars (at 50 pc), despite the opportunity to detect low EIRP levels from the nearest stars. Such a policy would be the opposite of looking under the lamppost.

We therefore entertain the adoption of a hybrid strategy for allocating exposure time. In this strategy, each star is assigned a nominal exposure time that achieves a uniform EIRP threshold. We adopt the stars at 25 pc for the fiducial exposure time of “1 exposure time unit”. Thus, the stars at 50 pc must receive an exposure time of 4 exposure time units.

However, this nominal strategy would require exposure times for the stars at 5 pc that would be only 1% as long as those at 50 pc (see **Figure 6**). If we spent 1 hour total exposing on a star at 50 pc we would spend only 36 seconds on stars at 5 pc. This strategy has several apparent weaknesses. The nearest stars would receive exposure times (~30 seconds) comparable to the slew time of the telescope. Also, we would miss the opportunity to expose somewhat longer on the nearest stars to achieve extraordinarily low EIRP detection thresholds, approaching radio leakage levels from Earth.

Figure 6 shows the histogram of integration times for all 1709 stars, assuming a strict rule that yields the same EIRP threshold for each star. The units of exposure time are normalized to the exposure time enjoyed by a star at 25 pc. Apparently, most stars require an exposure time (to achieve the same EIRP as stars at 25 pc) that is less than ~1.3 exposure time units. A tail of exposure times is apparent, stretching from 1.7 – 4 exposure time units, that would use considerable telescope time, but their numbers aren’t so large as to dominate the allocation of telescope time.

We thus propose to entertain a hybrid strategy. *The ~60 stars within 5 pc could receive 10x their nominal exposure (that would have yielded an equal EIRP threshold to all other stars).* For example, stars located 5 pc away would receive not 1% the exposure time of a star at 50 pc but instead 10% the exposure time, a boost of a factor of 10. Clearly these ~60 stars within 5 pc will still use only a small fraction of the available telescope time. We consider boosting their exposure time by more than 10x below.

Figure 7 shows the histogram of integration times (similar to Figure 6), but assuming a 10x boost of the integration times for all stars within 5 pc. Note that fewer stars that receive the shortest integration times (far left) as they now receive 10x their nominal exposure time.

Figure 8 shows the histogram of integration times (similar to Figures 6 and 7), but assuming a 25x boost of the integration times for all stars within 5 pc. Note fewer stars that receive the shortest integration times (far left) as they now receive 25x their nominal exposure time.

Figure 9 shows integration time vs B-V, to give a sense of how much telescope time will be devoted to each spectral of star along the main sequence. Note that the reddest stars (far right) receive only small integration times, because they are the nearby, M dwarfs. In contrast the bluest stars of spectral type, B, A, F, and early G, receive large amounts of exposure time due to their distances of 25-50 pc.

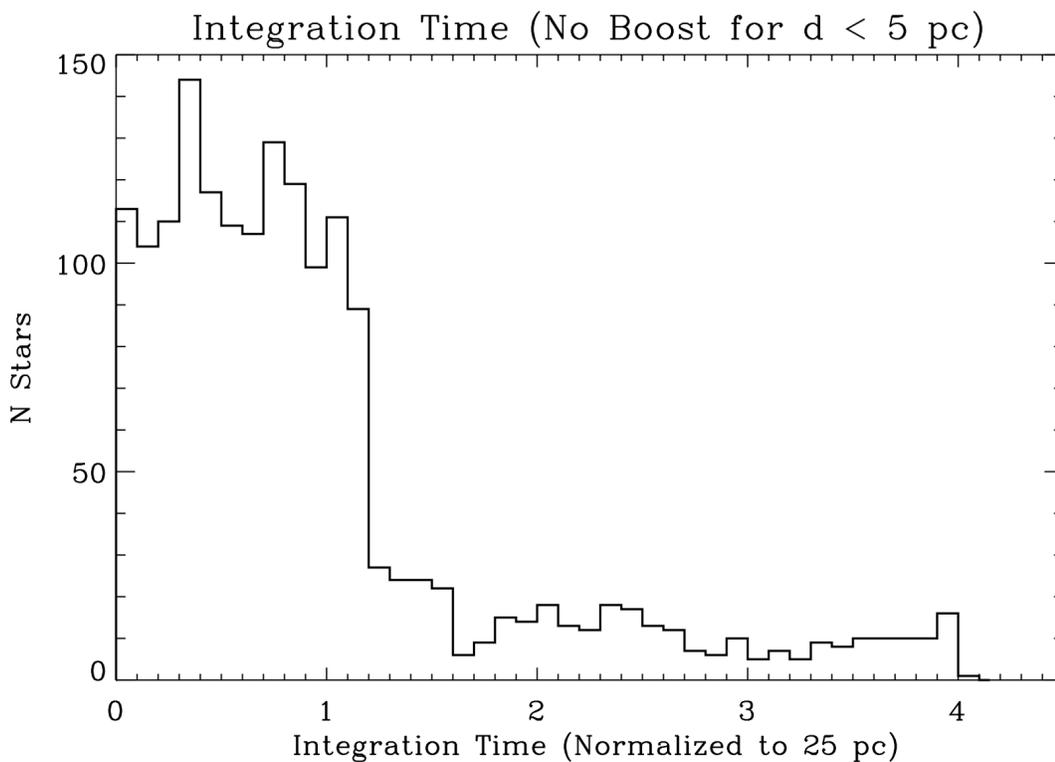


Figure 6. Histogram of exposure times assuming a strict policy of exposure times that accounts exactly for the distance to each star system, achieving a uniform EIRP for every star. The exposure times are normalized to stars at a distance of 25 pc. Those at 50 pc would receive 4x the fiducial exposure, and those at 2.5 pc would receive 1% the fiducial exposure time (of stars at 25 pc). This strategy allows the nearest stars to enjoy very little of the total telescope allocation and affords them very little gain from their proximity.

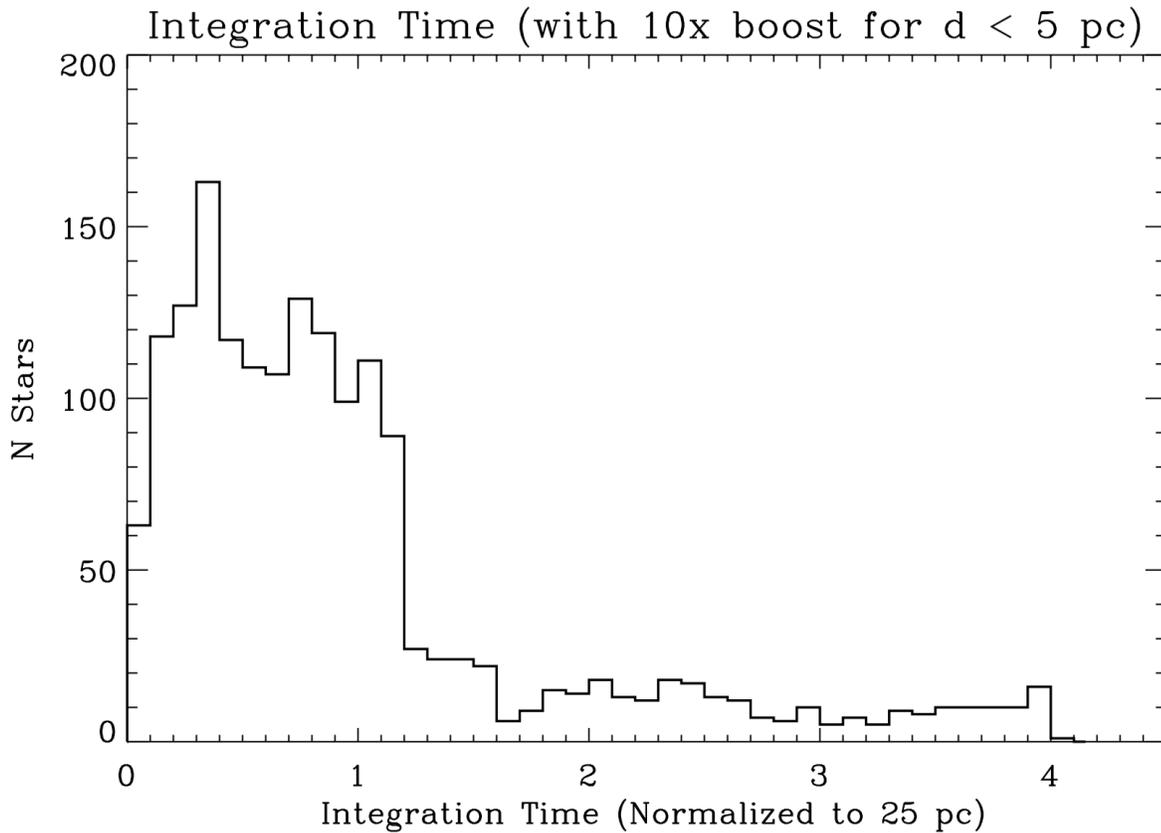


Figure 7. Histogram of exposure times assuming a hybrid policy of exposure times that accounts for the distance to each star system beyond 5 pc, achieving a uniform EIRP. However, for stars within 5 pc, the exposure times are multiplied by 10x, to achieve 10x the EIRP detection threshold of the stars beyond 5 pc. This strategy *boosts* the exposure time by 10x for the stars within 5 pc so that their EIRP detection threshold is 1/10 that of the more distant stars (5-50 pc). The exposure times (“Integration Time”) are normalized to stars at a distance of 25 pc. Those at 50 pc would receive 4x the fiducial exposure. But those stars at 2.5 pc would receive 1/10 the fiducial exposure (of stars at 25 pc), not 1/100. This strategy allows the nearest stars to enjoy more of the total GBT telescope allocation to gain from their proximity and still use only a small fraction of the total telescope allocation.

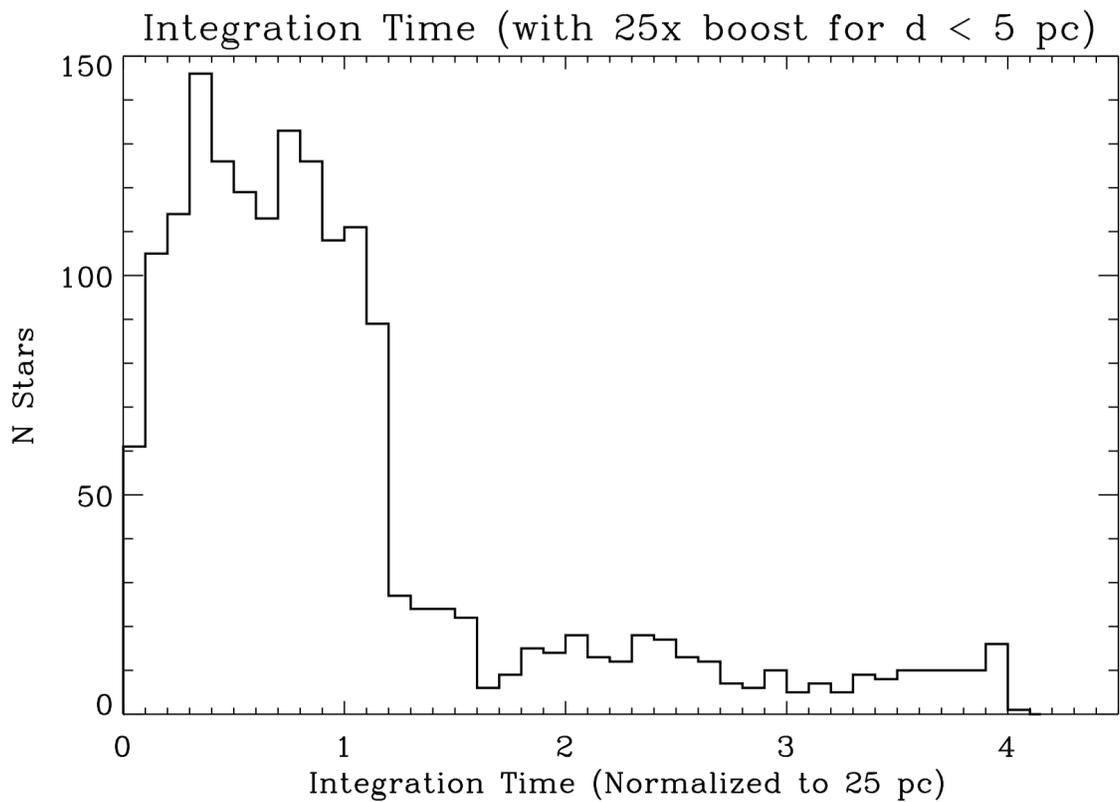


Figure 8. Same as Figure 7, but with 25x boost of exposure times for all stars within 5 pc. This distribution of exposure times isn't much different from those with no boost (Figure 6) or 10x boost (Figure 7) because the stars within 5 pc enjoy such tiny exposure times that boosting by 25x doesn't add up to much compared to stars at or beyond 25 pc.

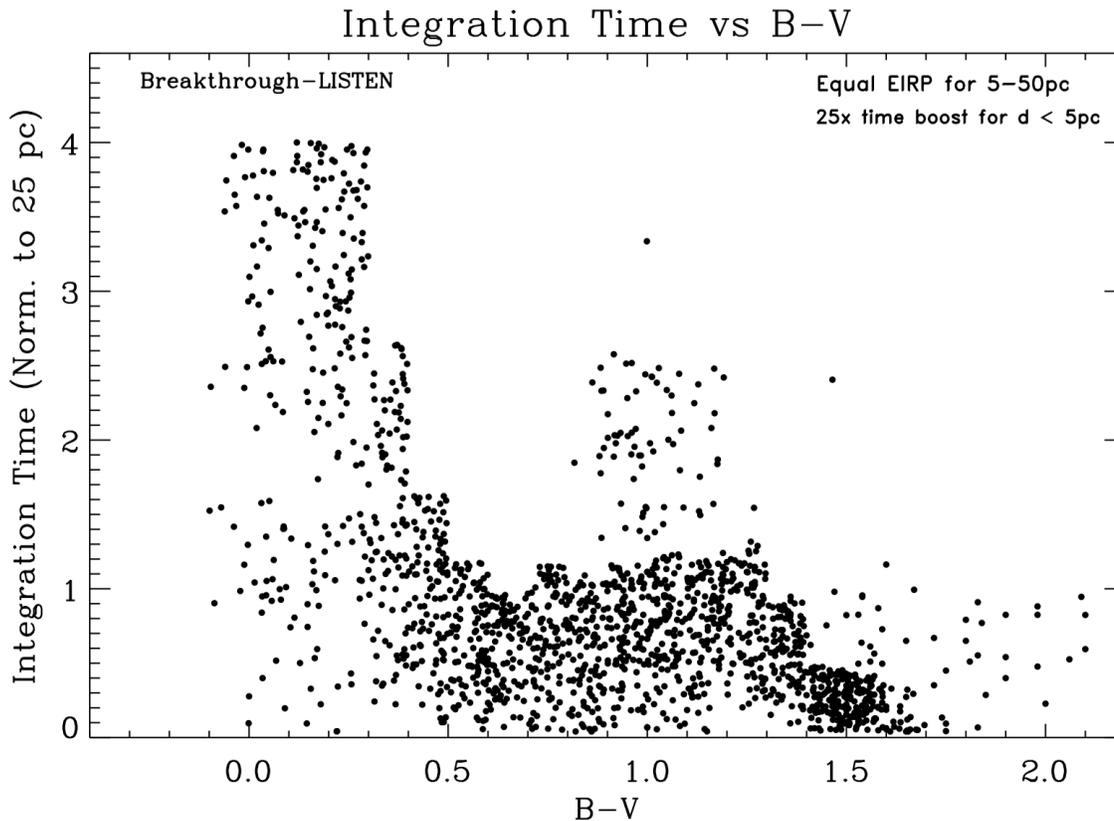


Figure 9. Integration times (with 10x boost for stars within 5 pc) vs B-V. Several domains are apparent. The stars with $B-V > 1.3$ (lower right) are M dwarfs that are mostly nearby, and thus require only short integration times. The stars with $B-V$ near 1.0 (middle) are the numerous K-type and early M-type dwarf stars that reside at 3-20 pc, and also the K-type giant stars that are mostly distant ($d > 25$ pc), requiring a broad range of exposure times. The stars with $B-V < 0.4$ (at left) are the F-, A-, B-type stars that are typically more distant, 30-50 pc, many requiring mostly large exposure times to reach nominal EIRP threshold.

5. Summary

It seems that this strategy of dividing the BL survey into two sub-samples has paid some dividends. All stars within 5 pc are included (all sky, north and south) and they can receive a boost in exposure times to yield lower EIRP detection thresholds (i.e. allowing the detection of weaker transmitters). The other sub-sample, at distances of 5-50 pc, nicely samples the main sequence and giant stars.

It seems that we may want to boost the exposure times of the stars within 5 pc by 25x, thereby achieving a detection EIRP threshold that is 25x lower than (1/25 the intrinsic power of) the stars located beyond 5 pc. With that 25x boost, stars at 5 pc enjoy exposure times exactly the same as stars at 25 pc, which seems like a good trade between spending telescope time (not much) and getting better EIRP thresholds (1/25 the power).

Obviously, there remains an opportunity to apply an arbitrary functional relationship to establish exposure times, yielding some variable EIRP threshold for the 1709 stars. It is worth discussion. But, there remains a valuable simplicity in achieving a touchstone EIRP level for the majority of the stars, and fixed “boost” in EIRP sensitivity for the nearest stars.