The Three-Dimensional Distribution of Galactic AGB Stars with ALLWISE

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1. Introduction

The formation of galaxies like the Milky Way was long thought to be a steady process that created a smooth distribution of stars. This standard view was exemplified by the Bahcall & Soneira (1980) and Gilmore et al. (1989) models, described in detail by, e.g., Majewski (1993). It was further motivated by observations of other galaxies, as well as what little information was available from *High Precision Parallax Collecting Satellite* (*HIPPARCOS*, Kovalevsky 1984) and smaller pencil-beam surveys. In these, the Milky Way is modeled by three discrete components described by simple analytic expressions: the thin disk, thick disk, and halo.

The advent of the *Sloan Digital Sky Survey* (SDSS, York et al. 2000) alleviated these limitations, providing accurate digital multi-band optical photometry across a quarter of the sky, as well as the largest optical spectroscopic catalog thus far known. This new influx of data enabled the development and application of photometric parallax methods, using color-magnitude relations to estimate stellar distances. In turn, this led to the large scale "tomography" of the Milky Way via stellar distributions in the 7-dimensional space spanned by spatial coordinates (Jurić et al. 2008), velocity components (Bond et al. 2010), and metallicity (Ivezić et al. 2008). The resulting maps revealed rich, complex substructure in the distribution of the Milky Way's stars (e.g. Ivezić et al. 2000; Yanny et al. 2000; Vivas et al. 2001; Newberg et al. 2002; Majewski et al. 2003; Belokurov et al. 2006; Grillmair 2006; Vivas & Zinn 2006), deeply shaking the existing view of the Galaxy.

In order to move forward from where SDSS tomography left off, we require observations that span an area larger than that of SDSS with Galactic objects that can be seen through interstellar dust out to large distances. Stars from the Asymptotic Giant Branch (AGB) are perfect candidates as probes to the Milky Way. AGB stars are represent the last stage of evolution for stars between 0.8 and 8 $M_\odot$ (Iben & Renzini 1983; Herwig 2005), so they are bound to reside throughout the galaxy wherever other stars are present. During this phase, they produce substantial stellar winds ($10^{-7} < \dot{M} < 10^{-4} M_\odot$ yr^{-1}, Olofsson et al. 2002) rich in SiO and amorphous carbon as they progress through being oxygen-rich to being carbon-rich. These winds collect into circumstellar shells that, when warmed by the stellar photosphere, shine brightly in the near- and mid-infrared (NIR & MIR respectively).

The *Wide-field Infrared Survey Explorer* (WISE, Wright et al. 2010; Cutri et al. 2012) is a space-based observatory that has imaged the entire sky in the MIR (3.4, 4.6, 12, and 22μm).

Additionally, WISE has been positionally matched to the Two-Micron All-Sky Survey (2MASS), a four-year mission characterizing the full sky in the NIR. Thus, the WISE catalog presents with hundreds of millions of sources with photometry of unprecedented sensitivity in the NIR and MIR– ideal for capturing AGB stars at Galactic distances. In Section 2, we describe in detail the data that we use for our study.

In Section 3, we describe the color-color criteria used to isolate AGB stars in the WISE dataset, and the color-magnitude relationships that were derived for these stars from the Large Magellanic Cloud and the Milky Way bulge. In Section 4, we describe the spatial density distribution of AGB candidates in the Milky Way. Our conclusions can be found in section 5.

2. Data Sources and Reduction

2.1. Data Sources

In order to analyze the physical distribution of AGB stars in the IR, we require reliable identifications of known AGB, stars to generate color-color selection criteria. We select AGB stars from three source catalogs: the *Optical Gravitational Lens Experiment-III Variable Star Catalog* (OGLE-III, Udalski et al. 2008; Soszyñski et al. 2009; Soszyński et al. 2011), the *MAssive Compact Halo Objects* project (MACHO, Alcock et al. 1997), and the SIMBAD Astronomical Database (Wenger et al. 2000). OGLE-III photometry for Long-Period Variables (LPVs) in the Small and Large Magellanic Clouds (SMC and LMC respsectively) was obtained between July 2001 and May 2009, with stars in the central 4.5-deg^2 of the LMC and SMC having an additional 5 observing seasons of photometry from OGLE-II. O-rich and C-rich AGB stars in OGLE-III were photometrically selected using reddening-free Wesenheit magnitudes, described in Soszyñski et al. (2009); Soszyński et al. (2011). Data reduction techniques are described in Udalski et al. (2008). The resulting samples yielded 46,467 AGB stars from the LMC (37,203 O-rich; 9,264 C-rich) and 6,509 stars from the SMC (3,727 O-rich; 2,782 C-rich). From MACHO we obtain the sample of SMC, LMC, and Galactic Bulge AGB stars used in Fraser et al. (2008) (14,861 stars). The sample of AGB stars from SIMBAD was obtained by querying for all objects classified as C-stars (18,656), S-stars (1,108), OH/IR stars (825), AGB stars (2,359), and Mira variables (9,608), for a total of 32,556 stars. The total sample of AGB stars is 100,393.

Since SDSS is an optical survey of unprecedented extent and sensitivity, we use SDSS spectroscopic catalogs to select contaminant sources for the NIR-MIR color-color fields of AGB stars. Data for active galactic nuclei (AGN; 19,184 objects), quasi-stellar objects (QSOs; 122,550 objects), and star forming/burst galaxies (820,272 objects total) were drawn from SDSS DR7, specifically from the NYU Value Added Galaxy Catalog[1] (Blanton et al. 2005, VAGC). Luminous Red Galax-

[1] http://sdss.physics.nyu.edu/vagc/

ies (LRGs) were selected from the SDSS Luminous Red Galaxy Survey (105,631 objects, Kazin et al. 2010). Data for stars in the SDSS stellar locus were drawn from the DR 9 SEGUE Stellar Parameters Pipeline (SSPP) (1,843,190 objects, Ahn et al. 2012).

In this study, we rely heavily on data from the ALLWISE extension of the WISE survey, combining data from the initial All-Sky Data Release, the 3-band cryogenic data release, and the NEOWISE post-cryogenic data release (Cutri et al. 2013). The initial WISEAll-Sky Data Release observed the sky between January and August 2010, observing the sky 1.2 times with four detectors, operating at 3.4, 4.6, 12, and 22μm. Hereon we refer to ALLWISE photometric bands at [3.4μm/4.6μm/12μm/22μm] as [$W1/W2/W3/W4$]. The positions of objects in the WISE catalog were calibrated to the 2MASS point source catalog. The 3-band cryogenic data release contains data from $W1$, 2, and 3, and surveyed 30% of the sky between August and October 2010. During the 3-band cryogenic survey, $W1$ and $W2$ operated with nearly the same sensitivity as during the full survey. Warming of the telescope reduced sensitivty in $W3$ and fully saturated $W4$. The NEOWISE post-cryogenic data release contains $W1$ and $W2$ measurements, with sensitivities close to those obtained during the full cryogenic phase. During this phase, WISE surveyed 70% of the sky. Data products from the post-cryogenic release included updated instrumental, astrometric, and photometric calibrations and reduction algorithms, resulting in much lower SNR. The overall total number of sources compiled into ALLWISE totals over 747.6 million.

2.2. Data Reduction

We use NASA/IPAC IRSA's `GATOR` tool[2] to positionally match SDSS, OGLE-III, MACHO, and SIMBAD to ALLWISE. We select only matches within 2" between our main sample of known AGB stars and ALLWISE. We further reduce our sample to unique matches to ALLWISE amongst OGLE-III, MACHO, and SIMBAD by selecting ALLWISE photometry for unique ALLWISE designations. All samples of AGB star matches were required to be brighter than the published 5σ faint limits of [16.83/15.6/11.32/8.0], as well as fainter than the saturation limits of [2.0/1.5/-3.0/-4.0] extrapolated from the wings of the PSFs for point sources, for [$W1/W2/W3/W4$] (Cutri et al. 2013). We require associations with 2MASS objects within 3", detections in 2MASS J, K_s, and all ALLWISE magnitudes as well as SNR > 3 in each ALLWISE band.

We do not enforce the same faint or saturation limits on our contaminant samples. As a show of the strength of our selection criteria, we seek to include matches to each contaminant with reasonable detections in ALLWISE, and magnitudes reliable enough to perform the necessary color selections. We limit our sample from the SDSS DR9 SSPP to objects within 0.5 dex of the $g'-r'$ vs. $g'-i'$ stellar locus (Davenport et al. 2014), SDSS SNR > 5, [$W1/W2/W3/W4$] SNR > 3, detections in 2MASS J and K_s bands, and one 2MASS association within 3". Objects from the NYU VAGC

[2]http://irsa.ipac.caltech.edu/cgi-bin/Gator/nph-scan?mission=irsa&submit=Select&projshort=WISE

were reduced with requirements of SNR > 3 for $[W1/W2/W3/W4]$, required detections for 2MASS J and K_s bands, and one 2MASS association within 3". LRGs were required to have SNR > 3 for $[W1/W2/W3]$, detections for 2MASS J and K_s bands, and one 2MASS association within 3". The restriction on $W4$ was dropped here, as it reduces the population of LRGs by an order of magnitude. The population for each sample from initial matching, as well as after the application of the ALLWISE faint limits, saturation limits, and 2MASS detection requirements are shown in Table 1.

Table 1: AGB and Contaminant Populations

Population	SIMBAD C stars	OH/IR stars	Miras	S stars	AGB stars
2" match	13,245	294	8,850	1,078	1,665
Reduced	3,327	165	6,218	865	1,121
Population	MACHO seq1	seq2	seq3	seq4	
2" match	5,193	3,441	2,548	2,931	
Reduced	927	642	263	336	
Population	OGLE C-rich	O-rich			
2" match	11,417	38,369			
Reduced	737	2515			
Population	Locus Stars	AGN	LRG	QSO	Galaxies
2" match	1,508,158	18,481	102,178	113,392	799,761
Reduced	168,045	9,652	7,717	18,360	125,869

3. Object Selection Criteria

We made color-color criteria to create a catalog of AGB candidates. We kept it simple to maximize the number of objects we'd retain while minimizing contamination from non-AGB objects.

4. AGB Candidate Distribution

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5. Conclusions

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