# The Three-Dimensional Distribution of Galactic AGB Stars with ALLWISE

Nicholas M. Hunt-Walker, Zeljko Ivezic, Andrew C. Becker

*University of Washington, Department of Astronomy, Seattle, WA 98195*

nmhw@uw.edu, ivezic@uw.edu, acbecker@uw.edu

## 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 22$\mu$m).

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 respspectively) 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 22$\mu$m. Hereon we refer to ALLWISE photometric bands at [3.4$\mu$m/4.6$\mu$m/12$\mu$m/22$\mu$m] 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 3" between our main sample of known AGB stars and ALLWISE. All samples of AGB star matches were required to be brighter than the published $5\sigma$ 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), with no confusion or contamination flags in [$W1/W2/W3/W4$]. We require only single 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. 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. The WISE color-color distributions for the AGB and contaminant samples are shown in Figure 1.

---

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

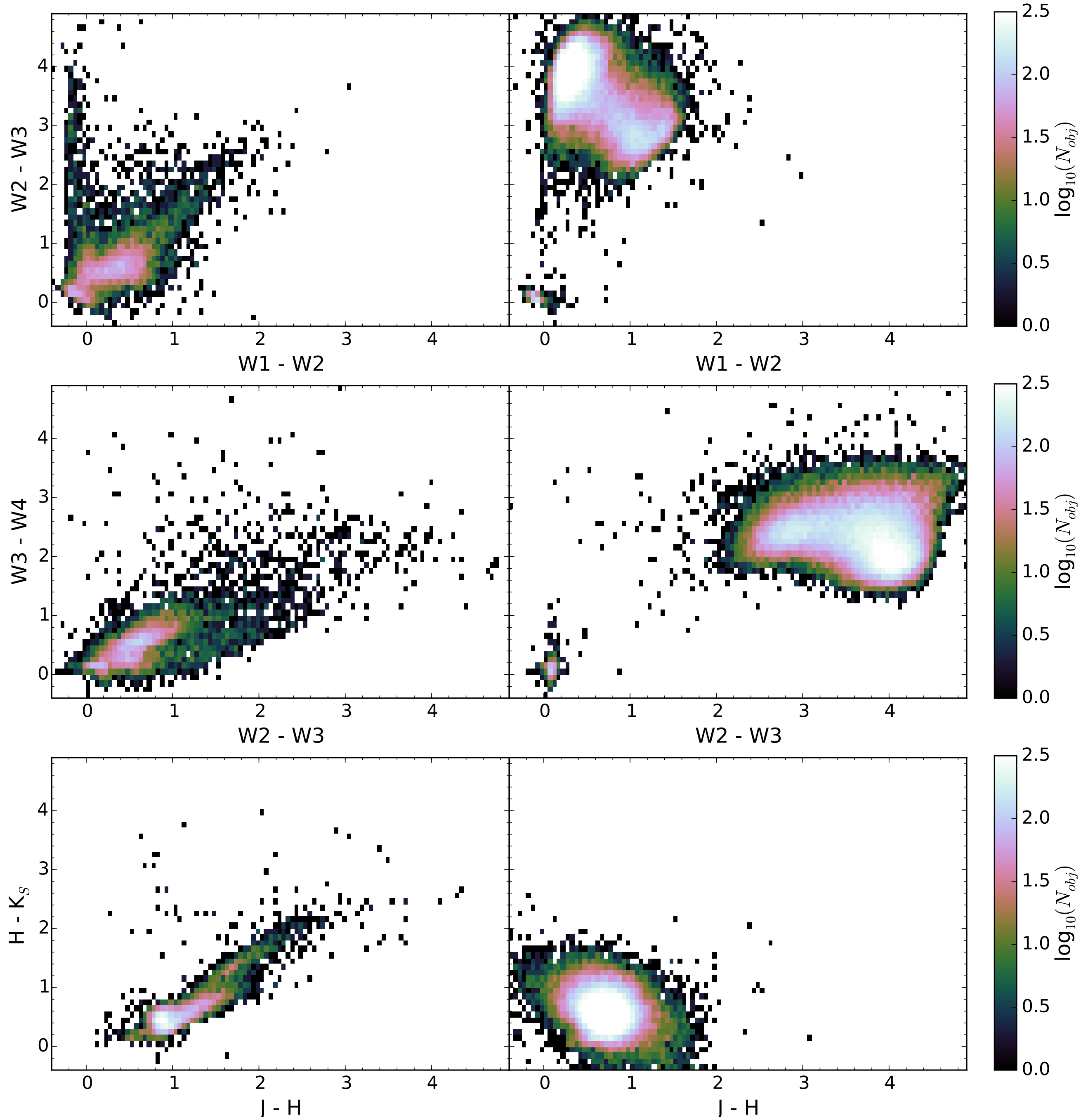


Fig. 1.— *Left:* Known AGB stars after data reduction. *Right:* All contaminants after data reduction.

Table 1: AGB and Contaminant Populations

| Population | SIMBAD AGB* | C* | Mira | OH/IR | S* |
|---|---|---|---|---|---|
| 3" match | 1,689 | 14,209 | 9,027 | 406 | 1,081 |
| Reduced | 684 | 1,782 | 3,241 | 43 | 511 |
| Population | MACHO seq1 | seq2 | seq3 | seq4 | |
| 3" match | 5,279 | 3,519 | 2,619 | 3,070 | |
| Reduced | 277 | 185 | 73 | 61 | |
| Population | OGLE-III C-rich | O-rich | | | |
| 3" match | 11,542 | 38,848 | | | |
| Reduced | 249 | 730 | | | |
| Population | DR12 SSPP | DR7 LRG | QSO | AGN | Galaxies |
| 3" match | 1,578,329 | 104,345 | 103,590 | 18,528 | 841,712 |
| Reduced | 67,508 | 84 | 3,977 | 1,069 | 44,314 |

## 3. Object Selection Criteria

We create color-color criteria to generate a catalog of AGB candidates. We seek to maximize AGB completeness while minimizing contamination from non-AGB objects to beneath the 1% level.

The color-color criteria for AGB selection are as follows:

$$(J - K_s) > 1.1 \tag{1}$$

$$(W2 - W3) > 0.3 \tag{2}$$

$$(W3 - W4) < -0.83(W2 - W3) + 3.37 \tag{3}$$

The criteria in (1) and (2) are primarily concerned with rejecting objects from the stellar locus, and other stars whose NIR spectra are dominated by the Rayleigh-Jeans tail (many covered by the sample of galaxies). Criteria in (3) also reject stars from the stellar locus, but primarily function to reject IR-bright extragalactic sources.

Sample completeness $\eta$ is defined as

$$\eta = \frac{N - n_{\rm missed}}{N}$$

where $N$ is the total number of objects in that sample, and $n_{\rm missed}$ is the number of objects outside of the applied boundaries. Figure 2 shows the distribution of completeness amongst AGB sources after the application of the above criteria. Sample contamination is typically defined as

$$\epsilon = \frac{n_{\rm spurious}}{n_{\rm selected}}.$$

where $n_{\rm spurious}$ is the number of spurious sources and $n_{\rm selected}$ is the total number of selected sources, including AGB objects and spurious objects (Ivezić et al. 2013). The contamination map is shown in Figure 3.

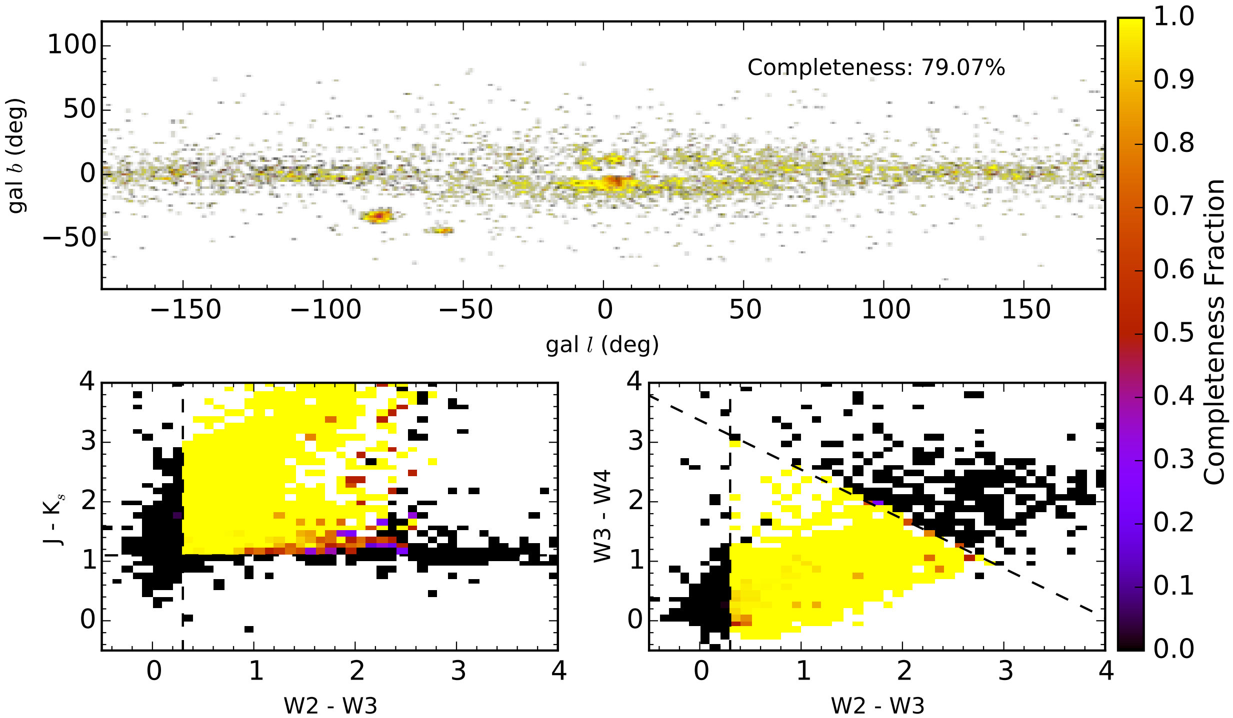


Fig. 2.— Words .

A fairly large issue for creating the boundaries are the O-rich stars. Either the objects from the OGLE O-rich AGB star catalog were mostly mis-matched to WISE, taking on colors of the stellar locus, or the issue is more physical. It could be that the warm O-rich AGB photospheres are still visible and not heavily enshrouded in dust, thus appearing similar to Main Sequence stars in the NIR. Previous work on warm O-rich AGB stars has shown that their circumstellar shells are not prominent, and their NIR photometry reflects the Rayleigh Jeans tail of a cool 2000-4000K blackbody (Dyck et al. 1974).

The results of the applied critiera are summarized in Table 2. Of the objects remaining in the sample, 52.94% of the AGBs have $|b| \leq 10°$.

## 4. AGB Candidate Distribution

Put words here

## 5. Conclusions

Put words here

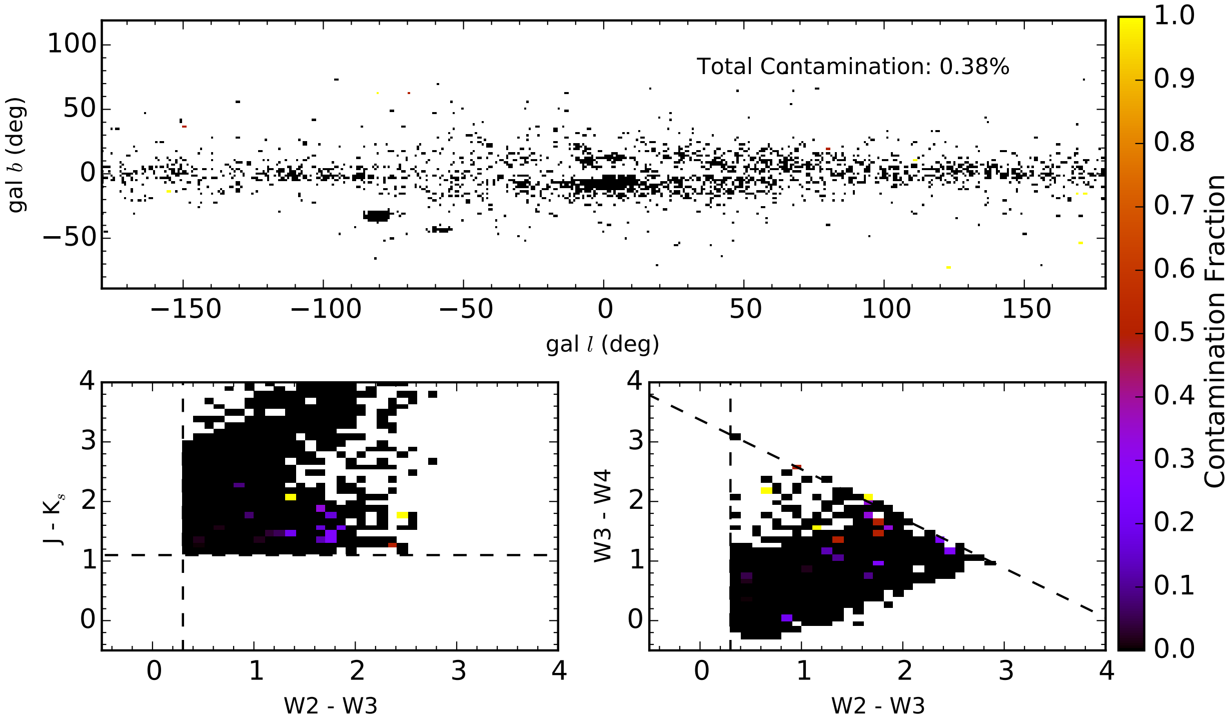


Fig. 3.— Words .

## REFERENCES


Ahn, C. P., et al. 2012, *Ap. J. Suppl.*, 203, 21

Alcock, C., et al. 1997, *Ap. J.*, 482, 89

Bahcall, J. N., & Soneira, R. M. 1980, *Ap. J. Suppl.*, 44, 73

Belokurov, V., et al. 2006, *Ap. J. (Letters)*, 642, L137

Blanton, M. R., et al. 2005, *A. J.*, 129, 2562

Bond, N. A., et al. 2010, *Ap. J.*, 716, 1

Cutri, R. M., et al. 2012, Explanatory Supplement to the WISE All-Sky Data Release Products, Tech. rep.

—. 2013, Explanatory Supplement to the AllWISE Data Release Products, Tech. rep.

Dyck, H. M., Lockwood, G. W., & Capps, R. W. 1974, *Ap. J.*, 189, 89

Fraser, O. J., Hawley, S. L., & Cook, K. H. 2008, *A. J.*, 136, 1242

Gilmore, G., Wyse, R. F. G., & Kuijken, K. 1989, *Ann. Rev. Astr. Ap.*, 27, 555

Table 2: Sample Completeness and Contamination

| | | | | | |
|---|---|---|---|---|---|
| Population | SIMBAD AGB* | C* | Mira | OH/IR | S* |
| Completeness | 89.62% | 72.11% | 95.62% | 39.53% | 22.31% |
| Population | MACHO seq1 | seq2 | seq3 | seq4 | |
| Completeness | 88.45% | 81.08% | 28.77% | 14.75% | |
| Population | OGLE-III C-rich | O-rich | **All AGB Stars** | | |
| Completeness | 73.09% | 70.68% | **79.07%** | | |
| Population | DR12 SSPP | DR7 LRG | Galaxies | QSO | AGN |
| Contamination | 0.56% | 0.00% | 0.00% | 0.07% | 0.00% |


Grillmair, C. J. 2006, *Ap. J. (Letters)*, 651, L29

Herwig, F. 2005, *Ann. Rev. Astr. Ap.*, 43, 435

Iben, Jr., I., & Renzini, A. 1983, *Ann. Rev. Astr. Ap.*, 21, 271

Ivezić, Ż., Connolly, A., VanderPlas, J., & Gray, A. 2013, Statistics, Data Mining, and Machine Learning in Astronomy

Ivezić, Ž., et al. 2000, *A. J.*, 120, 963

—. 2008, *Ap. J.*, 684, 287

Jurić, M., et al. 2008, *Ap. J.*, 673, 864

Kazin, E. A., et al. 2010, *Ap. J.*, 710, 1444

Kovalevsky, J. 1984, *Space Sci. Rev.*, 39, 1

Majewski, S. R. 1993, *Ann. Rev. Astr. Ap.*, 31, 575

Majewski, S. R., Skrutskie, M. F., Weinberg, M. D., & Ostheimer, J. C. 2003, *Ap. J.*, 599, 1082

Newberg, H. J., et al. 2002, *Ap. J.*, 569, 245

Olofsson, H., González Delgado, D., Kerschbaum, F., & Schöier, F. L. 2002, *Astr. Ap.*, 391, 1053

Soszyñski, I., et al. 2009, *Acta Astronomica*, 59, 239

Soszyński, I., et al. 2011, *Acta Astronomica*, 61, 217

Udalski, A., Szymanski, M. K., Soszynski, I., & Poleski, R. 2008, *Acta Astronomica*, 58, 69

Vivas, A. K., & Zinn, R. 2006, *A. J.*, 132, 714

Vivas, A. K., et al. 2001, *Ap. J. (Letters)*, 554, L33

Wenger, M., et al. 2000, *Astr. Ap. Suppl.*, 143, 9

Wright, E. L., et al. 2010, *A. J.*, 140, 1868

Yanny, B., et al. 2000, *Ap. J.*, 540, 825

York, D. G., et al. 2000, *A. J.*, 120, 1579

---