THEY MIGHT BE GIANTS: AN EFFICIENT COLOR-BASED SELECTION OF RED GIANT STARS

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ABSTRACT

We present a color-based method for identifying red giants based on Pan-STARRS grz and WISE W1 and W2 photometry. We utilize a subsample of bright stars with precise parallaxes from Gaia DR2 to verify that the color-based selection reliably separates dwarfs from giants. The selection is conservative in the sense that contamination is small (∼30%) but not all giants are included (the selection primarily identifies K giants). The color-based selection can be applied to stars brighter than W1 ≈ 16, more than two magnitudes fainter than techniques relying on shallower 2MASS photometry. Many streams and clouds are visible in the resulting sky maps, especially when binned by Gaia DR2 proper motions, including the Sagittarius stream, the Hercules-Aquila Cloud, the Eastern Banded Structure, Monoceros, and the Virgo Overdensity. In addition to the characterization of new and known stellar streams, we expect that this method for selecting red giants will enable detailed analysis of the diffuse stellar halo to distances exceeding 100 kpc.

Keywords: Galaxy: halo — Galaxy: kinematics and dynamics

1. INTRODUCTION

The stellar halo bears witness to the assembly of our Galaxy. The distribution of halo stars on small scales is highly structured, indicating that the majority have been accreted from satellite galaxies (e.g., Bell et al. 2006), as expected in the cold dark matter cosmological paradigm (e.g., White & Rees 1978; Bullock & Johnston 2005). In the inner ∼30 kpc, remnants of individual dwarf galaxies and globular clusters have been discovered as overdensities of old and metal-poor turn-off stars (Newberg et al. 2016; Grillmair & Carlin 2016 and references therein), and more recently via kinematics (e.g., Malhan et al. 2018).

The virial radius of the Milky Way extends beyond 250 kpc (e.g., Posti & Helmi 2018), but due to the scarcity of luminous tracers, the outer halo remains poorly charted. RR Lyrae, pulsating standard candles, have been used to map the largest volume of the Galactic halo, tracing the smooth component out to ∼110 kpc (Cohen et al. 2017), and remnants of disrupted dwarf galaxies between 10 and 100 kpc (e.g., Vivas & Zinn 2006; Watkins et al. 2009; Sesar et al. 2017a). In addition to requiring time series observations to detect RR Lyrae, they are also relatively rare, making it difficult to use them to trace lower mass populations (Sesar et al. 2017b). Other rare, luminous tracers have been used to map the outer halo including blue horizontal branch stars (BHB Deason et al. 2012, 2018b) and Carbon stars (Mauron et al. 2004; Mauron et al. 2008). A full account of the Milky Way’s accretion history will require mapping the halo with tracers that are both luminous and abundant.

Red giant branch stars are both relatively numerous and luminous and therefore would serve as an excellent tracer of the stellar halo. The key challenge is identifying them in photometric surveys. Red giants have similar optical colors as the much more numerous dwarfs of the same temperature; however, they can be separated with near-infrared photometry (e.g., Bessell & Brett 1988). NIR color-based selection was used to identify M giants and map not only the massive debris from the Sagittarius dwarf galaxy (e.g., Majewski et al. 2003), but also stellar streams and clouds from less massive progenitors (e.g., Rocha-Pinto et al. 2003, 2004), and identify very distant halo stars (Bochanski et al. 2014). Koposov et al. (2015) and Li et al. (2016) refined this selection method and detected parts of the Sagittarius stream in the highly crowded and high extinction plane of the Galaxy.

Previous work utilizing NIR color-based selection has focused on identifying M giants, which are both intrinsically luminous and clearly localized in 2MASS and WISE color-color diagrams. An advantage of this approach is that both 2MASS and WISE are all-sky surveys and so structure can be mapped in this way throughout the Galaxy. The disadvantages are two-fold: M giants are a relatively rare population, compared to e.g., K giants, and the use of 2MASS data restricts the usable data to $K_s < 13.5$ (equivalent to $W1 < 13.5$ for cool stars). WISE data extend at least 2.5 mag fainter than 2MASS, so a color-based method for selecting red giants that does not require 2MASS photometry would enable a view of structure in the Galaxy to much fainter limits than previous 2MASS-based catalogs. In this paper, we present such a method for a pure selection of (mostly K-type) giant stars relying only on Pan-STARRS and WISE photometry.

2. SELECTING GIANTS

We begin with a catalog of stars that is cross-matched between the Gaia mission (Gaia Collaboration et al. 2016), data release 2 (Gaia Collaboration et al. 2018), Pan-STARRS data release 1 (PS1 Chambers et al. 2016), and WISE W1 and W2 photometry (Wright et al. 2010; Cutri et al. 2013). The cross-matching was performed using the Large Survey Database framework (Juric et al. 2012) with a matching radius of < 1”. All photometry has been corrected for Galactic extinction using the Schlegel et al. (1998) dust maps. Where Gaia data
are used we require visibility\_periods\_used≥ 6 and
astrometric\_excess\_noise> 1.2γ(G) where γ(G) =
max[1,10^{0.2(G−18)}] (see Lindegren et al. 2018 for
details). When WISE data are used we require uncertain-
ties on W1 and W2 photometry to be 0 < σW1 < 0.1
and σW2 > 0. Following Li et al. (2016), we also apply
the following criteria to ensure high-quality photometry:
\texttt{ext\_flag=0} and \texttt{cc\_flags=’0’}.

It is well known that a single color is generally unable
to separate the K and M dwarfs from the K and M gi-
ants. This ambiguity presents a critical bottleeneck to
studying the stellar halo because along any line of sight
a flux-limited sample will be overwhelmingly dominated
by the much more numerous dwarfs. A combination of
broadband colors that could reliably separate the dwarfs
and giants would enable a much cleaner view of the outer
regions of the Galaxy. Previous work along these lines
have used 2MASS JHK_s photometry (Majewski et al.
2003), or a combination of 2MASS and WISE photome-
try (Koposov et al. 2015) to select M giants.

Inspired by previous efforts, we explored a variety of
color-color cuts utilizing Pan-STARRS and WISE broad-
band colors. After some experimentation we settled on
the following selection:

\begin{equation}
\begin{aligned}
-0.4 &< W1 – W2 < 0.0 \\
g - r &< 1.1 \\
1.9 &< z - W1 < 2.5 \quad (1)
\end{aligned}
\end{equation}

W1 – W2 selection produces a very clear bifurcation in
\( g - r \) vs. \( z - W1 \) which we identify as sequences of
dwarfs and giants (see Figure 1). The additional cuts iso-
late the giant sequence in that space. We chose to
avoid the use of 2MASS photometry because 2MASS is
much shallower than WISE and our goal is to go as faint
as possible. The fairly conservative \( z - W1 > 1.9 \) selec-
tion was motivated by the larger photometric scatter at
fainter magnitudes. The depth in our case is limited by
WISE: at \( W1 = 16 \) the typical uncertainty on \( W1 \) is 0.06
mag and at \( W2 = 15 \) the typical uncertainty on \( W2 \) is
0.07 mag.

An illustration of the selection method is presented in
Figure 1. We select stars with Galactic latitude \( b > 80^\circ \)
to minimize the effects of reddening and \( 11 < W1 < 13 \)
so that uncertainties on the Gaia DR2 parallaxes are
small. We then apply the \( W1 – W2 < 0.0 \) cut and plot
the remaining stars in the left panel. The selection box
in the \( g - r \) vs. \( z - W1 \) space is indicated by the dashed
lines. In the middle panel we show only stars with a
parallax of \( 0.5 \text{ mas} \) (\( > 2 \text{ kpc} \)), and in the right panel
those stars with \( 0.5 \text{ mas} \) (\( < 2 \text{ kpc} \)). 70% of the stars in
the selection box have \( 0.5 \text{ mas} \). As we will see in a
moment, stars with low parallaxes are giants, indicating
that our color selection has a purity of \( ∼ 70\% \).

In the middle and right panels we also include the gi-
ant (\( \log g < 3 \)) and dwarf (\( \log g > 4 \)) sequences from
MIST isochrones at 10 Gyr (Choi et al. 2016). Stars in the
middle panel are similar to low-metallicity giants, as
expected for a halo population, while stars in the right
panel are similar to solar metallicity dwarfs, as expected
for the local disk population. The models are systemati-
cally bluer in \( g - r \) for the reddest colors; this is a known
limitation of the color-temperature relations used in the
models (Choi et al. 2016).

According to the MIST isochrones, the color selection
is identifying the middle portion of the RGB (e.g., K
giants) over the metallicity range \( -2 < [Z/H] < 0 \). The
coldest stars (M giants) are omitted due to the \( g - r > 1.1 \)
cut. This cut was necessary in order to avoid substantial
contamination from the M dwarf locus, which turns verti-
cal in Figure 1 at \( g - r > 1.1 \). The absolute magnitudes
of the RGB stars range from \( -5 ≤ M_{W1} ≤ -2 \). The WISE
data reaches \( W1 ≈ 15.5 \) before photometric uncertain-
ties compromise the color selection. This translates into
a reach of \( > 100 \text{ kpc} \) for this color selection technique.

In Figure 2 we examine in more detail the purity of the
proposed color selection. In the top panel we show the
distribution of parallaxes for a sample of stars with
\( 11 < W1 < 13 \) and \( b > 80^\circ \). The overall sample is com-
pared to subsamples defined via a simple color cut of
\( 0.7 < g - r < 1.1 \), and our \( grW1W2 \) color selection.
This bright sample of stars has small parallax uncertain-
ties and so one sees a clear bimodality in the distribution

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Selection of giants via color-color cuts. Each panel shows log(number) of stars in the (de-reddened) \( g - r \) vs. \( z - W1 \) color space selected to have \( W1 – W2 < 0, 11 < W1 < 13 \), and \( 80^\circ < b < 90^\circ \). Two sequences are clearly seen in the left panel, which shows all stars. The middle and right panels show stars selected to have parallaxes \( < 0.5 \text{ mas} \) (middle) and \( > 0.5 \text{ mas} \) (right). Our selection
box used to identify giants is marked by the dashed lines. Also shown in the middle and right panels are the giant (\( \log g < 3 \)) and dwarf (\( \log g > 4 \)) sequences from a 10 Gyr MIST isochrone.

![Figure 2](https://example.com/figure2.png)

**Figure 2.** In the top panel we show the distribution of parallaxes for a sample of stars with \( 11 < W1 < 13 \) and \( b > 80^\circ \). The overall sample is compared to subsamples defined via a simple color cut of \( 0.7 < g - r < 1.1 \), and our \( grW1W2 \) color selection. This bright sample of stars has small parallax uncertain-
ties and so one sees a clear bimodality in the distribution
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Figure 2. Top panel: Distribution of parallaxes for stars with $11 < W_1 < 13$ and $b > 80^\circ$. The entire population is compared to stars with $0.7 < g - r < 1.1$, and our giant-based color selection (labeled as grzW1W2). These bright stars have small parallax uncertainties and so the stars with $\pi \approx 0.0$ can be confidently associated with greater distances. The greater distance combined with the narrow magnitude range suggests that the low-parallax stars are giants. This is confirmed in the bottom panel, which shows the color-magnitude diagram for all stars (shown as a Hess diagram with a logarithmic color stretch) and for the giant-based color selection. Stars with $\pi < 0.5$ mas are clearly giants, and they comprise 70% of the grzW1W2 color-selected stars. Stars with negative parallaxes were assigned a nominal parallax of 0.01 mas for display purposes.

Figure 3. Comparison between parallax-only selection (top panel), parallax plus M giant selection from Koposov et al. (2015) (middle panel), and parallax plus our K giant color selection (bottom panel), for stars with $11 < W_1 < 13.5$. The maps show log(number) of stars in $0.5^\circ \times 0.5^\circ$ bins. The color stretch is the same for the middle and lower panel. The total number of stars in each map is shown in the title of each panel.

We explored the completeness of these color cuts using the SDSS SEGUE sample (Yanny et al. 2009), which includes stellar parameters (Lee et al. 2008). We restrict the SEGUE sample in several respects, including $|b| > 20^\circ$, $W_1 < 15.5$, and requiring a quality flag of ‘nmnm’. Following Xue et al. (2014), we identify K giants with $0.5 < g - r < 1.3$. We furthermore require $[\text{Fe/H}] > -2$, as some stars have what appear to be unrealistically low metallicities (e.g., some stars have $[\text{Fe/H}] \approx -4$). We selected giants based on the clear separation from the dwarf sequence in log $g - T_{\text{eff}}$ space. We discovered that some of the resulting K giant stars had $\pi > 0.5$ mas, which, given their apparent magnitudes, places them squarely on the photometric dwarf sequence. Such stars are removed. We find that our color cuts select 80% of the SEGUE K giants with $T_{\text{eff}} < 4500K$. In other words, our selection method identifies cooler K giants with high completeness. The completeness drops rapidly for warmer giants, which is not surprising given the selection of red stars with both $g - r$ and $z - W1$ cuts.

3. RESULTS

We applied the color-based selection of red giants to the entire cross-matched Gaia DR2, PS1, and WISE catalogs. The sky coverage of PS1 limits us to Dec $> -30^\circ$. We have also removed stars with $\pi > 0.5$ mas as an additional filter against foreground stars.

Figure 3 compares binned maps of stars selected only by parallax (top panel) and those with both a parallax and two color-based selection techniques (middle and bottom panels). Here we include stars with $11 < W_1 < 13.5$ and omit data near the plane ($|b| < 10^\circ$). In the middle panel we implement the Koposov et al. (2015) M giant selection, which utilizes 2MASS JK$_s$ and WISE W1 and W2 photometry (these authors restricted their analysis to $11 < W_1 < 13.5$, which motivated our choice.
Figure 4. Maps of red giant stars selected according to the color cuts in Figure 1. Regions where $|b| < 10^\circ$ are omitted. The panels show stars in two W1 magnitude ranges. The maps show log(number) of stars in $0.5^\circ \times 0.5^\circ$ bins. The Sagittarius stream (labeled) is prominent in the top and middle panels. The Eastern Banded Structure (EBS) is visible and labeled in the top panel. In the bottom panel we use our new color selection. It is clear that even for these relatively bright stars, where the mean parallax uncertainty is 0.05 mas, that a parallax selection alone is insufficient to identify the distant giants. This is not surprising — a star at 10 kpc has a true parallax of 0.1 mas and so a typical parallax uncertainty (for the stars in this figure) of 0.05 mas implies that it will be difficult to separate a star at 10 kpc from the much more numerous foreground dwarfs. In contrast, the parallax plus color-based selection reveals a variety of structures and overdensities, the most prominent being the Sagittarius (Sgr) stream.

Comparison of the middle and bottom panels reveals the differences between an M giant-based selection (middle) and a K giant based selection (bottom). There are approximately $26 \times$ more stars in the lower panel compared to the middle panel, even though the magnitude range is the same, owing largely to the fact that K giants are much more numerous than M giants. Because of this, one can see more streams and structures in the lower panel. As we will see below, a second advantage of the Pan-STARRS and WISE color selection employed here is that we can extend to fainter limits than selections based on 2MASS and WISE. We do note that an advantage of the color selection in the middle panel is that it can be applied to the entire sky thanks to the all-sky 2MASS and WISE datasets.

In Figure 4 we show maps of the red giant stars in two W1 magnitude bins. Data in the plane ($|b| < 10^\circ$) have been omitted. These maps are rich in structure. The most obvious feature is the Sgr stream which stretches across the entire map in the top panel. In the middle panel the Sgr stream has broken up into pieces, and in the bottom panel Sgr is not easily visible, except perhaps for the overdensity near (260,-10); see below for details.
Figure 5. Maps of red giant stars in a wide magnitude range (10 < $W_1$ < 15.5) in bins of proper motion. Rows are sorted by increasing $\mu_\delta$ while columns are sorted by increasing $\mu_\alpha$ (in units of mas yr$^{-1}$). The maps show the number of stars in 0.5° × 0.5° bins. See Figure 6 for a continuation of the proper motion bins. Many known streams and stellar overdensities appear in these proper motion maps.

At these fainter magnitudes we are likely probing the more distant components of the Sgr stream, as seen in previous work (Majewski et al. 2003) and predicted by models (e.g., Law & Majewski 2010; Dierickx & Loeb 2017).

In the top panel there are several additional easily visible features including the stream extending from (100,40) to (160,90). This structure is at an approximately constant Galactic latitude of $b \approx 35^\circ$ and corresponds to Feature B in Slater et al. (2014), also known as the Eastern Banded Structure reported in Grillmair (2011).

In Figures 5 and 6 we show the giant star maps in proper motion bins. In these maps the structures in our Galaxy appear most dramatic. In addition to the Sgr stream, which appears in many panels (see Sohn et al. 2015 for previous proper motion measurements at various locations along the Sgr stream using Hubble Space Telescope), one clearly sees the structure referred to as either a part of the Monoceros Ring (Slater et al. 2014) or the Eastern Banded Structure (Grillmair 2011) in the 0 < $\mu_\alpha$ < 1, −1 < $\mu_\delta$ < 1 bins. This feature extends from (100,40) to (180,90). Deason et al. (2018a) used SDSS-Gaia proper motion measurements to demonstrate that this structure is part of a complex network of substructures in the Galactic anti-center region with a likely origin due to some perturbation of the Galactic disk.

The Hercules-Aquila Cloud (Belokurov et al. 2007; Simion et al. 2014, 2018) appears at 290 < R.A. < 360 and −30 < Dec < 40 in the proper motion range 0 < $\mu_\alpha$ < 1, −3 < $\mu_\delta$ < 0. The plume of stars in the bin $-2 < \mu_\alpha < -1$, −1 < $\mu_\delta$ < 0, north of Sgr, may also be associated with Hercules-Aquila. The proper motion gradient of this structure, extending thousands of sq. degrees across the sky, is remarkable and supports the scenario outlined in Simion et al. (2018) that the Hercules-Aquila Cloud is part of a much larger debris structure originating from an old, well-mixed accretion event.

There is a large cloud centered at (150,-10) in the proper motion bin $-1 < \mu_\alpha < 0$, $-2 < \mu_\delta < -1$, with a plausible northward extension in the bin $-1 < \mu_\alpha < 0$, $-2 < \mu_\delta < -1$. Many known streams and stellar overdensities appear in these proper motion maps.
−3 < µ < −2. This structure is very likely associated with the Virgo Overdensity (Newberg et al. 2002; Bonaca et al. 2012; Duffau et al. 2014; Vivas et al. 2016; Sesar et al. 2017b). If so, then the map in Figure 5 offers the most complete on-sky extension of the Virgo Overdensity to-date.

There are additional features in these proper motion maps whose association with known structures is less obvious. We leave a detailed analysis of the structure in these diagrams to future work.

4. SUMMARY

In this paper we have presented a new color-based method for selecting K-type red giants that is based on Pan-STARRS grz and WISE W1 and W2 photometry. Gaia DR2 parallaxes of a bright subsample confirms that this selection identifies giants with low contamination from dwarfs (≈30%). Comparison to the SEGUE sample of spectroscopically-confirmed giants reveals that the completeness of our color selection is ≈80% for cool (T_\text{eff} < 4500K) giants. The resulting maps display a rich variety of structure both as a function of R.A. and Dec. and proper motion.

Our proposed color selection offers several benefits over previous NIR color-based techniques that focused on selection of M giants (e.g., Majewski et al. 2003; Koposov et al. 2015). First, M giants, though more luminous, are rarer than K giants, and so a selection aimed at identifying the latter class of objects will result in a higher density of tracers. Moreover, previous M giant selections relied on 2MASS photometry, which is approximately 2.5 mag shallower than WISE. By avoiding 2MASS we are therefore able to reach at least 2 mag deeper than previous giant-based color selections. The major drawback to our approach is that it requires grz photometry, for which complete coverage exists only at Dec > −30°.

In the future we will investigate and characterize the many features visible in the maps. These maps can also be used to study the diffuse stellar halo at large distances. The requirement that these stars be detected in WISE W1 and W2 means that they are relatively bright, and so will be straightforward to follow up with high resolution spectroscopy on 6 – 10m telescopes. Pan-STARRS lim-
ited the sky coverage to Dec > −30° but the technique can be easily extended to the south with Dark Energy Survey data. Furthermore, the overall depth can be extended by utilizing the extended WISE 4 yr data.

We emphasize that the color cuts adopted herein are not necessarily optimal for selecting red giants as simple trial and error was used to arrive at the final selection. The success of our adopted selection suggests that more sophisticated techniques (e.g., Mints & Hekker 2017; Anderson et al. 2017) should have even greater success at identifying red giants, so long as NIR data are employed.

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REFERENCES

Anderson, L., Hogg, D. W., Leistedt, B., Price-Whelan, A. M., & Bovy, J. 2017, arXiv:1706.08056
Bell, E. F., Zucker, D. B., Belokurov, V., Sharma, S., Johnston, K. V., Bullock, J. S., Hogg, D. W., Jahnke, K., de Jong, J. T. A., Beers, T. C., Evans, N. W., Grebel, E. K., Ivezić, Ž., Koposov, S. E., Rix, H.-W., Schneider, D. P., Steinmetz, M., & Zolotov, A. 2008, ApJ, 680, 295
Belokurov, V., Evans, N. W., Bell, E. F., et al. 2007, ApJ, 657, L89
Bessell, M. S. & Brett, J. M. 1988, PASP, 100, 1134
Bochanski, J. J., Willman, B., Caldwell, N., Sanderson, R., West, A. A., Strader, J., & Brown, W. 2014, ApJ, 790, L5
Bonaca, A., Juric, M., Ivezić, Ž., et al. 2012, AJ, 143, 105
Bullock, J. S. & Johnston, K. V. 2005, ApJ, 635, 931
Chambers, K. C., Magnier, E. A., Metcalfe, N., et al. 2016, arXiv:1612.05560
Choi, J., Dotter, A., Conroy, C., et al. 2016, ApJ, 823, 102
Cohen, J. G., Sesar, B., Bahnhöfer, S., He, K., Kulkarni, S. R., Prince, T. A., Bellm, E., & Laher, R. R. 2017, ApJ, 849, 150
Cutri, R. M. et al. 2013, VizieR Online Data Catalog, 2328
Deason, A. J., Belokurov, V., Evans, N. W., et al. 2012, MNRAS, 425, 2840
Deason, A. J., Belokurov, V., & Koposov, S. E. 2018a, MNRAS, 473, 2428
—. 2018b, ApJ, 852, 118
Dierickx, M. I. P. & Loeb, A. 2017, ApJ, 836, 92
Duffau, S., Vivas, A. K., Zinn, R., Méndez, R. A., & Ruiz, M. T. 2014, A&A, 566, A118

Gaia Collaboration, Brown, A. G. A., Vallenari, A., Prusti, T., de Bruijne, J. H. J., Babusiaux, C., & Baller-Jones, C. A. L. 2018, arXiv:1804.09365
Gaia Collaboration, Prusti, T., de Bruijne, J. H. J., Brown, A. G. A., et al. 2016, A&A, 595, A1
Grillmair, C. J. 2011, ApJ, 738, 98
Grillmair, C. J. & Carlin, J. L. 2016, in Astrophysics and Space Science Library, Vol. 420, Tidal Streams in the Local Group and Beyond, ed. H. J. Newberg & J. L. Carlin, 87
Juric, M. 2012, LSD: Large Survey Database framework, Astrophysics Source Code Library
Koposov, S. E., Belokurov, V., Zucker, D. B., Lewis, G. F., Ibata, R. A., Olszewski, E. W., López-Sánchez, Á. R., & Hyde, E. A. 2015, MNRAS, 446, 3110
Law, D. R. & Majewski, S. R. 2010, ApJ, 714, 229
Lee, Y. S., Beers, T. C., Sivarani, T., et al. 2008, AJ, 136, 2022
Li, J., Smith, M. C., Zhong, J., et al. 2016, ApJ, 823, 59
Lindegren, L., Hernandez, J., Bombrun, A., et al. 2018, ArXiv e-prints
Majewski, S. R., Skrutskie, M. F., Weinberg, M. D., & Osteheimer, J. C. 2003, ApJ, 599, 1082
Malhan, K., Ibata, R. A., & Martin, N. F. 2018, arXiv:1804.11339
Mauro, N. 2008, A&A, 482, 151
Mauro, N., Azzopardi, M., Gigoyan, K., & Kendall, T. R. 2004, A&A, 418, 77
Mints, A. & Hekker, S. 2017, A&A, 604, A108
Newberg, H. J. & Carlin, J. L., eds. 2016, Astrophysics and Space Science Library, Vol. 420, Tidal Streams in the Local Group and Beyond
Newberg, H. J., Yanny, B., Rockosi, C., et al. 2002, ApJ, 569, 245
Posti, L. & Helmi, A. 2018, ArXiv e-prints
Rocha-Pinto, H. J., Majewski, S. R., Skrutskie, M. F., & Crane, J. D. 2003, ApJ, 594, L115
Rocha-Pinto, H. J., Majewski, S. R., Skrutskie, M. F., Crane, J. D., & Patterson, R. J. 2004, ApJ, 615, 732
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Sesar, B., Banholzer, S. R., Cohen, J. G., Martin, N. F., Grillmair, C. J., Levitan, D., Laher, R. R., Ols, E. O., Surace, J. A., Kulkarni, S. R., Prince, T. A., & Rix, H.-W. 2014, ApJ, 793, 135
Sesar, B., Henry, N., Dierickx, M. I. P., Fardal, M. A., & Rix, H.-W. 2017a, ApJ, 844, L4
—. 2017b, ApJ, 844, L4
Simion, I. T., Belokurov, V., Irwin, M., & Koposov, S. E. 2014, MNRAS, 440, 161
Simion, I. T., Belokurov, V., Skrutskie, M. F., Sheffield, A., & Johnston, K. V. 2018, MNRAS, 476, 3913
Slater, C. T., Bell, E. F., Schlafly, E. F., et al. 2014, ApJ, 791, 9
Sohn, S. T., van der Marel, R. P., Carlin, J. L., Majewski, S. R., Kaliliavajil, N., Law, D. R., Anderson, J., & Siegel, M. H. 2015, ApJ, 803, 56
Vivas, A. K. & Zinn, R. 2006, AJ, 132, 714
Vivas, A. K., Zinn, R., Farmer, J., Duffau, S., & Pfing, Y. 2016, ApJ, 831, 165
Watkins, L. L., Evans, N. W., Belokurov, V., et al. 2009, MNRAS, 398, 1757
White, S. D. M. & Rees, M. J. 1978, MNRAS, 183, 341
Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, AJ, 140, 1868
Xue, X.-X., Ma, Z., Rix, H.-W., et al. 2014, ApJ, 784, 170
Yanny, B., Rockosi, C., Newberg, H. J., et al. 2009, AJ, 137, 4377