D1005+68: A New Faint Dwarf Galaxy in the M81 Group

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Abstract

We present the discovery of d1005+68, a new faint dwarf galaxy in the M81 Group, using observations taken with the Subaru Hyper Suprime-Cam. d1005+68’s color–magnitude diagram is consistent with a distance of $3.98^{+0.39}_{-0.43}$ Mpc, establishing group membership. We derive an absolute $V$-band magnitude, from stellar isochrone fitting, of $M_V = -7.94^{+0.38}_{-0.50}$, with a half-light radius of $r_h = 188^{+39}_{-41}$ pc. These place d1005+68 within the radius–luminosity loci of Local Group and M81 satellites and among the faintest confirmed satellites outside the Local Group. Assuming an age of 12 Gyr, d1005+68’s red giant branch is best fit by an isochrone of [Fe/H] = $-1.90 \pm 0.24$. It has a projected separation from nearby M81 satellite BK5N of only 5 kpc. As this is well within BK5N’s virial radius, we speculate that d1005+68 may be a satellite of BK5N. If confirmed, this would make d1005+68 one of the first detected satellites-of-a-satellite.

Key words: galaxies: dwarf – galaxies: individual (d1005+68, M81 Group)

1. Introduction

The past decade has seen an awakening in the field of dwarf galaxy discovery. Large photometric surveys such as the Sloan Digital Sky Survey (SDSS), the Panoramic Survey Telescope Rapid Response System (Pan-STARRS), and the Dark Energy Survey (DES) have permitted the discovery of >30 faint and ultrafaint dwarf galaxy (UFD) candidates in the Local Group (e.g., Belokurov et al. 2006; Martin et al. 2013; Drlica-Wagner et al. 2016; Homma et al. 2016). These discoveries have informed the nearly two-decade-old “missing satellites problem” (hereafter MSP; Klypin et al. 1999). This apparent tension between the low-end halo mass function prediction, by $\Lambda$CDM, and the considerably flatter slope of the Milky Way dwarf galaxy luminosity function is a sensitive probe of dark matter properties and galaxy formation in the lowest-mass dark matter halos (e.g., Macciò et al. 2010; Brooks et al. 2013). Yet, with improved understanding, new puzzles have emerged. An apparent dearth of luminous high-velocity subhalos—the “too big to fail” problem (hereafter TBTF; Boylan-Kolchin et al. 2011)—is an extension of MSP that is not alleviated by the discovery of UFDs (see Simon & Geha 2007, Macciò et al. 2010, Font et al. 2011, and Brooks et al. 2013 for discussion of possible solutions to MSP and TBTF). Furthermore, mounting evidence suggests that both the Milky Way’s and M31’s satellites form potentially planar structures (Pawlowski et al. 2013). Though $\Lambda$CDM predicts anisotropic accretion due to infall along cosmic filaments (e.g., Li & Helmi 2008), potentially resulting in planar satellite distributions (Sawala et al. 2016), the thinness of the Local Group planes remains difficult to replicate.

$\Lambda$CDM predicts that all galaxy halos host subhalos, the most massive of which will host luminous satellites. Consequently, many of the satellites around Milky Way–mass galaxies also likely possess, or possessed before infall, their own orbiting subhalos. These “satellites-of-satellites” are difficult to detect, owing to their intrinsic faintness. Recent work suggests that several of the Milky Way satellites nearest to the Magellanic Clouds may be satellites of the Clouds themselves (Drlica-Wagner et al. 2016), with possibly >30% of Milky Way satellites originating around the Large Magellanic Cloud (LMC; Jethwa et al. 2016).

It is clear that our understanding of dwarf galaxy populations in the $\Lambda$CDM paradigm is currently limited. A key hurdle is that our understanding of dwarf galaxy luminosity functions, spatial distributions, and properties is almost entirely confined to the Local Group. Characterization of satellite populations around other Local Group analogs is crucial if we are to obtain a complete description of low-mass galaxy formation.

Propelled by the advent of wide-field imagers on large telescopes, discovery and characterization of faint “classical dwarfs” ($M_V < -10$) has become possible in nearby galaxy groups and clusters using large area (approaching 100 deg$^2$) diffuse light surveys (e.g., Chiboucas et al. 2009; Müller et al. 2015; Muñoz et al. 2015; Ferrarese et al. 2016). Observationally expensive, smaller area deep surveys of resolved stellar populations in nearby galaxy groups are bringing even fainter dwarf galaxies within reach (e.g., Sand et al. 2015; Carlin et al. 2016; Crenjević et al. 2016; Toloba et al. 2016).

In this Letter, we present the discovery of a faint dwarf spheroidal galaxy in the M81 group, d1005+68 (following the naming convention of Chiboucas et al. 2013), detected as an overdensity of stars in observations taken with the Subaru Hyper Suprime-Cam. At $M_V = -7.9$ (see Section 3), d1005+68 is one of the faintest confirmed galaxies discovered outside of the Local Group.

2. Detection

We use observations taken with the Subaru Hyper Suprime-Cam (HSC; Miyazaki et al. 2012) through NOAO Gemini–Subaru exchange time (PI: Bell, 2015A-0281). The observations
The stripe at bright magnitudes is composed of Milky Way foreground stars. The yellow lines are 12 Gyr PARSEC isochrones (Bressan et al. 2012), with $[\text{Fe/H}] = -2.1$ (left), $[\text{Fe/H}] = -1.7$ (center), and $[\text{Fe/H}] = -1.2$ (right), shown here for reference. Below left: the $g - r$ vs. $r - i$ color–color diagram of photometrically identified sources. The stellar locus (High et al. 2009) is shown as a yellow curve. RGB stars defined by our morphological, CMD, and stellar locus criteria (Section 2) are shown as either blue, green, or red points, corresponding to their metallicity bin. The darkest region is the galaxy locus. Right: a cutout of the map of M81’s stellar halo in resolved RGB stars (A. Smercina et al. 2017, in preparation). The colors correspond to the metallicity bins defined on the CMD in the top left figure. The known galaxies in the field are labeled. d1005+68 is located at the bottom left of the map, indicated by a black arrow. It appears as a significant overdensity of blue (metal-poor) RGB stars, very near to the dwarf spheroidal, BK5N.

![Figure 1](image)

**Figure 1.** Top left: the $g - r$ vs. $r$ CMD (de-redened) of all stars (see Section 2) in the Subaru field, separated into $\sim 0.01$ mag bins. The RGB is encapsulated within the drawn polygon, which has been divided into three metallicity bins by eye, blue being the most metal-poor. The blue locus is likely a combination of young Helium burners and unresolved high-redshift foreground galaxies. The stripe at bright magnitudes is composed of Milky Way foreground stars. The yellow lines are 12 Gyr PARSEC isochrones (Bressan et al. 2012), with $[\text{Fe/H}] = -2.1$ (left), $[\text{Fe/H}] = -1.7$ (center), and $[\text{Fe/H}] = -1.2$ (right), shown here for reference. Bottom left: the $g - r$ vs. $r - i$ color–color diagram of photometrically identified sources. The stellar locus (High et al. 2009) is shown as a yellow curve. RGB stars defined by our morphological, CMD, and stellar locus criteria (Section 2) are shown as either blue, green, or red points, corresponding to their metallicity bin. The darkest region is the galaxy locus. Right: a cutout of the map of M81’s stellar halo in resolved RGB stars (A. Smercina et al. 2017, in preparation). The colors correspond to the metallicity bins defined on the CMD in the top left figure. The known galaxies in the field are labeled. d1005+68 is located at the bottom left of the map, indicated by a black arrow. It appears as a significant overdensity of blue (metal-poor) RGB stars, very near to the dwarf spheroidal, BK5N.

| Parameter | Value |
|-----------|-------|
| $\alpha$(J2000) | $10^\text{h}05^\text{m}31.82^\text{s} \pm 1.1$ |
| $\delta$(J2000) | $-68^\circ14'56''56 \pm 5.95$ |
| $D_{\text{TRGB}}$ | $3.98 \pm 0.39$ Mpc |
| $M_\phi$ | $-7.94 \pm 0.38$ |
| $r_h$ | $0.97 \pm 2.0$ |
| $s_h$ | $188 \pm 41$ pc |
| $\log(M_\phi/M_\odot)$ | $5.40 \pm 0.22$ |
| $[\text{Fe/H}]$ | $-1.90 \pm 0.24$ |

**Notes.**

* Isochrone fitting, assuming $D_{\text{TRGB}}$.
* Current stellar mass, assuming 40% mass loss.
* Metallicity of best-fit isochrone, assuming $[\alpha/\text{Fe}] = 0.25$.

As the dwarf galaxies of interest are low surface brightness and possess little diffuse emission, we detect dwarf candidates by resolving them into individual stars. At the distance of M81 (3.6 Mpc; Radburn-Smith et al. 2011), only stars in the top $\sim25\%$, or tip of the RGB (TRGB), are visible. TRGB stars are relatively numerous, and as they trace the old stellar population of galaxies, their number can be scaled to a total luminosity with modest uncertainty (Harmsen et al. 2017).

At our survey depths, contaminants—high-redshift background galaxies—dominate. The majority of these galaxy contaminants must be removed in order to reach the surface brightness sensitivity necessary to detect faint dwarf satellites ($\mu_V \lesssim 28$ mag arcsec$^{-2}$). We reject galaxies using a combined morphology and color cut; such a process sacrifices completeness in order to dramatically suppress contamination (this will be revisited in Section 3). To be defined as a star, a source must satisfy two criteria: (1) FWHM $\lesssim 0.96$ across all three bands (we will consider less stringent cuts later), and (2) consistent with the $g - r$ versus $r - i$ stellar locus within $\sigma_{g-r}$ (the photometric uncertainty) $+ 0.2$ mag (intrinsic scatter; High et al. 2009). Next, we locate stars on the RGB from the $g - r$ versus $r$ color–magnitude diagram (CMD) and divide them into three metallicity bins using simple polygonal boundaries (see Figure 1).

d1005+68 stands out as a significant overdensity of metal-poor stars in the sparse, metallicity-binned RGB star map of M81’s...
stellar halo (Figure 1), with nine RGB stars visible in a $1' \times 1'$ region centered on d1005+68. To quantify the prominence of this overdensity against the surrounding diffuse stellar halo, we extract 500 $1' \times 1'$ (independent) regions from a 0.14 deg$^2$ region south of d1005+68, away from the stellar debris associated with the tidal disruption of NGC 3077. We compute the discrete probability distribution of the number of RGB stars returned in each region and fit it to a Poisson distribution, $p(N|\lambda)$. From the best-fit Poisson distribution, we take a mean background of $\lambda = 0.38 \pm 0.03$ RGB stars arcmin$^{-2}$. Integrating over the best-fit distribution, and correcting for the number of independent 1 arcmin$^{-2}$ regions (10$^3$) in the target footprint, we obtain a cumulative probability of drawing nine RGB stars arcmin$^{-2}$ of $4.2 \times 10^{-6} \pm 3.5 \times 10^{-6}$. Placed into terms of standard error, this is a 4.5–5$\sigma$ detection. Thus, we expect to detect such random overdensities in our target footprint. In the following section, we discuss the derivation of d1005+68’s properties, which are summarized in Table 1. Its position relative to other M81 Group members is shown in the map of M81’s stellar halo in Figure 1. In Figure 2 we show the i-band image of d1005+68 with detected RGB stars encircled, as well as the curve of growth.

3. Properties

The $g - i$ versus $i$ CMD of probable member stars of d1005+68 are shown in Figure 3. We define membership based on the shape of the curve of growth (Figure 2, bottom right panel), where the background-subtracted profile asymptotes to a $\sim$-constant value. In contrast to the stringent cut used for detection of the dwarf, we use broader criteria for membership determination and the derivation of the dwarf’s properties. At low signal-to-noise, the measured sizes of objects is subject to significant scatter, causing tight tolerances on size to reject many true stars. Consequently, the stars shown on the CMD were chosen using the same color constraint as for detection, but with a looser size constraint—FWHM in $x$ and $y \leq 0.03$. Also shown in Figure 3 are CMDs of nearby (in projection) dwarf galaxy BK5N—both full and randomly down-sampled to the number of observed stars in d1005+68.

The centroid, half-light radius, and number of member stars (and therefore luminosity) are the averages of a range of values estimated by varying the size cut between 0.06 and 1.34, the number of stars used to define the position of the center (relative to the optical center) between 5 and 12, and the Poisson background value (see Section 2). For each iteration, the number of member stars are determined using the turnover of the background-subtracted curve of growth, from which the half-light radius is also derived. The mean values of the centroid and half-light radius can be found in Table 1, along with the standard deviations of the various iterations.

The TRGB can be used as a robust distance estimator, due to its near-constant luminosity ($M_I = -4.04$ in the Johnson-Cousins system) at low metallicities (Bellazzini et al. 2001).
The TRGB for d1005+68’s CMD (see Figure 3) was calculated as in Monachesi et al. 2016, but also includes the completeness in the model luminosity function (LF), \( \phi \) (see below), as in Makarov et al. (2006):

\[
\phi(m|\mathbf{x}) = \int \psi(m'|\mathbf{x}) \, e(m|m') \, \rho(m') \, dm',
\]

where \( \psi \) is the true LF, \( e \) is the Gaussian error kernel, \( \rho \) is the completeness, and \( \mathbf{x} \) is the vector of model parameters that we fit. See Appendix C of Monachesi et al. (2016) for details. The completeness was tabulated in 0.3 mag \( i \)-band bins using the area in common with GHOSTS and smoothed with a three-bin boxcar (the smoothing has no effect on the derived TRGB magnitudes). We find a TRGB of \( L_{\text{TRGB}} = 24.48_{-0.17}^{+0.17} \). Using an SDSS “Lupton prescription”\(^7\) in the JC system, this corresponds to \( d_{\text{TRGB}} = 23.96_{-0.20}^{+0.20} \), or a distance modulus of \( m - M = 28.00_{-0.20}^{+0.20} \). Thus, we derive a distance to d1005+68 of \( 3.98_{-0.33}^{+0.35} \) Mpc.

d1005+68’s luminosity was estimated using the number of stars visible to a certain \( i \)-band “depth” below the TRGB. To convert the number of observed stars to a total number of stars above this \( i \)-band limit, we use the GHOSTS fields for M81 (Radburn-Smith et al. 2011) to compute the stellar completeness in the Subaru field, as a function of \( i \)-band magnitude, for our three size cuts (0.06, 0.084, 1.034). For all three size cuts, we estimate a total number of 32 ± 6 RGB stars to a depth of \( \sim 1.2 \) mag below the TRGB and 25 ± 4 to a depth of \( \sim 1.1 \) mag below the TRGB. We then randomly sample our best-fit isochrone in that magnitude range given a Chabrier (2003) stellar initial mass function (IMF). We record the resulting number of RGB stars drawn at each stellar mass and compute a probability distribution of drawing the observed number of stars at each mass, at the given RGB depth. We obtain a most probable initial mass of \( \log_{10}(M_*/M_\odot) = 5.62 \), which, after the standard 40% mass-loss correction (Bruzual & Charlot 2003), corresponds to a current stellar mass of \( \log_{10}(M_*/M_\odot) = 5.40 \) or \( M_\star = 2.5 \times 10^5 M_\odot \). We then convert the stellar mass distribution to a \( V \)-band luminosity, while randomly varying the number of stars in each isochrone, at a fixed stellar mass. Accounting for the variance in the different depths considered, as well as sampling variance along the IMF, we obtain a \( V \)-band luminosity of \( M_V = -7.94_{-0.38}^{+0.38} \). The primary uncertainties on this estimate come from our TRGB distance range and the width of the best-fit stellar mass distribution.

To estimate the metallicity, we fit a suite of PARSEC stellar isochrone models (Bressan et al. 2012) with a fixed 12 Gyr age, from \( Z = 0.0001 \)–0.001. The best-fit isochrone, for the \( g - i \) versus \( i \) CMD, corresponds to a metallicity of \( Z = 0.0004 \). Assuming \( [\alpha/Fe] = 0.25 \), this corresponds to \( [Fe/H] = -1.90 \). For each iteration in the centroid calculation (above) we draw 10 bootstrap samples and compute the best-fit isochrone for each case. We then combine the standard deviation of the resulting distribution with the TRGB distance uncertainties. We obtain a final metallicity estimate of \( [Fe/H] = -1.90 \pm 0.24 \).

d1005+68 has a projected separation from M81 of 1°22, or, using the distance to M81, 76.4 kpc. Using the adopted TRGB

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\( ^7 \) https://www.sdss3.org/dr8/algorithms/sdssUBVRITransform.php

Figure 3. Left: the color–magnitude diagram of d1005+68. Stars shown are identified with the 0′064 size cut (see Section 3), extending to \( \sim 0′5 \) or \( \sim 3r_0 \). The TRGB is shown as a red line, with the 90% confidence shown as the red shaded region. The three blue curves on each diagram correspond to the best-fit 12 Gyr isochrones at each distance bound, with respective metallicities (from left to right) of \([Fe/H] = -1.76\) (green), \(-1.90\) (blue), and \(-2.02\) (orange). Center left: the CMD of BK5N in RGB stars, with \( \sim 100 \) detected RGB stars. Center right: BK5N’s CMD, randomly down-sampled to match the number of member stars in d1005+68. Right: the \( i \)-band completeness function, \( \phi \).
are shown for reference. Our derived M81 Group data are compiled from the catalog of McConnachie (2012), from the recent slew of Dark Energy Survey (Bechtol et al. 2015; Drlica-Wagner et al. 2015; Koposov et al. 2015) and Pan-STARRS (Laevens et al. 2015) discoveries, and from other isolated discoveries (Belokurov et al. 2014; Kim et al. 2015; Homma et al. 2016). M81 Group data are compiled from Karachentsev et al. (2000), Lianou et al. (2010), and Chiboucas et al. (2013). In the absence of $M_V$ and $r_h$ uncertainties in the literature, typical Local Group uncertainties of 20% have been adopted for M81 members. d1005+68 is shown as a black star. Lines of constant surface brightness are shown for reference. Our derived $r_h$ and $M_V$ for d1005+68 place it well within the locus of Local Group satellites, while it is one of the faintest members of the M81 Group.

![Figure 4. Half-light radius–luminosity diagram for Milky Way, M31, Local Group, and M81 Group satellites. Milky Way satellites are shown as blue circles, M31 satellites as red circles, general Local Group members (outside the virial radius of MW or M31) as green circles, and M81 members as filled purple circles. Local Group data are compiled from the catalog of McConnachie (2012), from the recent slew of Dark Energy Survey (Bechtol et al. 2015; Drlica-Wagner et al. 2015; Koposov et al. 2015) and Pan-STARRS (Laevens et al. 2015) discoveries, and from other isolated discoveries (Belokurov et al. 2014; Kim et al. 2015; Homma et al. 2016). M81 Group data are compiled from Karachentsev et al. (2000), Lianou et al. (2010), and Chiboucas et al. (2013). In the absence of $M_V$ and $r_h$ uncertainties in the literature, typical Local Group uncertainties of 20% have been adopted for M81 members. d1005+68 is shown as a black star. Lines of constant surface brightness are shown for reference. Our derived $r_h$ and $M_V$ for d1005+68 place it well within the locus of Local Group satellites, while it is one of the faintest members of the M81 Group.](https://example.com/figure4.png)

distance to d1005+68 of $3.98^{+0.39}_{-0.43}$ Mpc, this corresponds to a large range in possible 3D distances. The projected physical separation between d1005+68 and the nearby (on the sky) dwarf spheroidal BK5N is only $\sim$5 kpc at the distance of BK5N (3.78 Mpc; Karachentsev et al. 2000). Assuming a stellar mass for BK5N of $\sim$$10^7 M_\odot$ ($M_V = -11.33$; Caldwell et al. 1998) and extrapolating from the stellar mass–halo mass relation of Behroozi et al. (2013), the virial radius of BK5N is likely $\sim$40 kpc. Therefore, were d1005+68 at a similar distance as BK5N, it would be well within BK5N’s virial radius. In support of this, the CMD of d1005+68 is well approximated by a random sampling of BK5N’s CMD, as in Figure 3. However, the 3D separation could be much higher when factoring in the uncertainty in d1005+68’s TRGB distance.

4. Discussion and Closing Remarks

In this Letter, we presented a new faint dwarf galaxy, d1005+68, with properties consistent with being a satellite of the M81 Group. It was detected as a $5\sigma$ overdensity in our 3.5 deg$^2$ Subaru Hyper Suprime-Cam survey of M81’s resolved stellar halo. We find that the CMD is best fit by an isochrone of age 12 Gyr and metallicity [Fe/H] = $-1.90 \pm 0.24$. d1005+68 has projected physical distances from M81, NGC 3077, and BK5N of $\sim$76 kpc, 40 kpc, and 5 kpc, respectively. The estimated heliocentric TRGB distance of $3.98^{+0.39}_{-0.43}$ Mpc provides strong evidence for group membership; however, the high uncertainties prohibit accurate estimates of 3D separation from other group members. Its current stellar mass, determined from isochrone fitting, is $M_\star = 2.5^{+1.7}_{-0.8} \times 10^5 M_\odot$, corresponding to an absolute V-band magnitude of $M_V = -7.94^{+0.38}_{-0.50}$.

Figure 4 shows d1005+68 in context of Local Group and M81 Group members. d1005+68 is among the faintest confirmed galaxies discovered outside of the Local Group—similar in brightness to M81 group member d0944+69 (Chiboucas et al. 2013; $M_V = -8.05$ with no claimed uncertainty), NGC 2403 member MADCASH J074238+652501-dw (Carlin et al. 2016; $M_V = -7.7 \pm 0.7$), Centaurus group member Dw5 (Crnojević et al. 2016; $M_V = -7.2 \pm 1.0$), and Fornax cluster member Fornax UFD1 (Lee et al. 2017; $M_V = -7.6 \pm 0.2$)—and probes the very faintest end of the known M81 satellite luminosity function.

The projected separation between d1005+68 and BK5N of 5 kpc is well within the estimated virial radius of BK5N ($\sim$40 kpc). With our highly uncertain TRGB distance (due to scarcity of stars) and the similarity between the two CMDs (Figure 3), this introduces the possibility that d1005+68 is a satellite of BK5N. If confirmed (via more accurate distance estimates and line of sight velocity information), this would make it the first satellite-of-a-satellite discovered outside of the Local Group.

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References

Axelrod, T., Kantor, J., Lupton, R. H., & Pierfederici, F. 2010, Proc. SPIE, 7740, 774015
Bechtol, K., Drlica-Wagner, A., Balbinot, E., et al. 2015, ApJ, 807, 50
Behroozi, P. S., Wechsler, R. H., & Conroy, C. 2013, ApJ, 770, 57
Bellazzini, M., Ferraro, F. R., & Pancino, E. 2001, ApJ, 556, 635
Belokurov, V., Irwin, M. J., Koposov, S. E., et al. 2014, MNRAS, 441, 2124
Belokurov, V., Zucker, D. B., Evans, N. W., et al. 2006, ApJL, 647, L111
Boylan-Kolchin, M., Bullock, J. S., & Kaplinghat, M. 2011, MNRAS, 415, L40
Bressan, A., Marigo, P., Girardi, L., et al. 2012, MNRAS, 427, 127
Brooks, A. M., Kuhlen, M., Zolotov, A., & Hooper, D. 2013, ApJ, 765, 22
Brown, G., & Charlot, S. 2003, MNRAS, 344, 1000
Caldwell, N., Armandroff, T. E., Da Costa, G. S., & Seitzer, P. 1998, AJ, 115, 535
Carlin, J. L., Sand, D. J., Price, P., et al. 2016, ApJL, 828, L5
Chabrier, G. 2003, PASP, 115, 763
Chiboucas, K., Jacobs, B. A., Tully, R. B., & Karachentsev, I. D. 2013, AJ, 146, 126
Chiboucas, K., Karachentsev, I. D., & Tully, R. B. 2009, AJ, 137, 3009
Cioni, R. L. M., Sand, D. J., Spekkens, K., et al. 2016, ApJL, 823, 19
Drlica-Wagner, A., Bechtol, K., Allam, S., et al. 2016, ApJL, 833, L5
Drlica-Wagner, A., Bechtol, K., Rykoff, E. S., et al. 2015, ApJ, 813, 109
Ferrarese, L., Côte, P., Sánchez-Janssen, R., et al. 2016, ApJ, 820, 16
Font, A. S., Benson, A. J., Bower, R. G., et al. 2011, MNRAS, 417, 1260
Harmsen, B., Monachesi, A., Bell, E. F., et al. 2017, MNRAS, 466, 1491
High, F. W., Stubbs, C. W., Rest, A., Stalder, B., & Challis, P. 2009, AJ, 138, 110
Homma, D., Chiba, M., Okamoto, S., et al. 2016, ApJ, 832, 21
Jethwa, P. E., Erkal, D., & Belokurov, V. 2016, MNRAS, 461, 2212
Karachentsev, I. D., Karachentseva, V. E., Dolphin, A. E., et al. 2000, A&A, 363, 117
Kim, D., Jerjen, H., Mackey, D., Da Costa, G. S., & Milone, A. P. 2015, ApJL, 804, L44
Klypin, A., Kravtsov, A. V., Valenzuela, O., & Prada, F. 1999, ApJ, 522, 82
Koposov, S. E., Belokurov, V., Torrealba, G., & Evans, N. W. 2015, ApJ, 805, 130
Laevens, B. P. M., Martin, N. F., Ibata, R. A., et al. 2015, ApJL, 802, L18
Lee, M. G., Jang, I. S., Beaton, R., et al. 2017, ApJL, 835, L27
Li, Y.-S., & Helmi, A. 2008, MNRAS, 385, 1365
Lianou, S., Grebel, E. K., & Koch, A. 2010, A&A, 521, A43
Maccinì, A. V., Kang, X., Fontanot, F., et al. 2010, MNRAS, 402, 1995
Magnier, E. A., Schlaufy, E., Finkbeiner, D., et al. 2013, ApJS, 205, 20
Makarov, D., Makarova, L., Rizzi, L., et al. 2006, AJ, 132, 2729
Martin, N. F., Schlaufy, E. F., Slater, C. T., et al. 2013, ApJ, 779, L10
McConnachie, A. W. 2012, AJ, 144, 4
Miyazaki, S., Komiyama, Y., Nakaya, H., et al. 2012, Proc. SPIE, 8446, 84460Z
Monachesi, A., Bell, E. F., Radburn-Smith, D. J., et al. 2016, MNRAS, 457, 1419
Müller, O., Jerjen, H., & Binggeli, B. 2015, A&A, 583, A79
Muñoz, R. P., Eisenhauer, P., Puzia, T. H., et al. 2015, ApJL, 813, L15
Pawlowski, M. S., Kroupa, P., & Jerjen, H. 2013, MNRAS, 435, 1926
Radburn-Smith, D. J., de Jong, R. S., Seth, A. C., et al. 2011, ApJS, 195, 18
Sand, D. J., Spekkens, K., Cioni, R. L. M., et al. 2015, ApJL, 812, L13
Sawala, T., Frenk, C. S., Fattahi, A., et al. 2016, MNRAS, 457, 1931
Schlaufy, E. F., & Finkbeiner, D. P. 2011, ApJ, 737, 103
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJL, 500, 255
Simon, J. D., & Geha, M. 2007, ApJ, 670, 313
Toloba, E., Sand, D. J., Spekkens, K., et al. 2016, ApJL, 816, L5