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# ANDROMEDA X, A NEW DWARF SPHEROIDAL SATELLITE OF M31: PHOTOMETRY

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## ABSTRACT

We report the discovery of Andromeda X, a new dwarf spheroidal satellite of M31, based on stellar photometry from the Sloan Digital Sky Survey. Using follow-up imaging data we have estimated its distance and other physical properties. We find that Andromeda X has a dereddened central surface brightness of $\mu_{V,0} \sim 26.7$ mag arcsec$^{-2}$ and a total apparent magnitude of $V_{tot} \sim 16.1$, which at the derived distance modulus, $(m - M)_0 \sim 24.12$–$24.34$, yields an absolute magnitude of $M_V \sim -8.1 \pm 0.5$; these values are quite comparable to those of Andromeda IX, a previously discovered low-luminosity M31 satellite. The discoveries of Andromeda X and of numerous other extremely faint satellites around M31 and the Milky Way in the past few years suggest that such objects may be plentiful in the Local Group.

*Subject headings:* galaxies: dwarf — galaxies: evolution — galaxies: individual (Andromeda IX, Andromeda X) — Local Group

## 1. INTRODUCTION

In hierarchical cold dark matter (CDM) models, large galaxies like the Milky Way and M31 form from the merger and accretion of smaller systems. Such models, while successful at large scales, predict at least 1–2 orders of magnitude more low-mass dark subhalos at the present epoch than the observed abundance of dwarf galaxies (e.g., Klypin et al. 1999; Moore et al. 1999; Benson et al. 2002a). This discrepancy, the "missing satellite" problem, is one of the most serious obstacles for matching CDM theory to observations.

A number of solutions have been proposed to address the problem, at least qualitatively. Star formation in low-mass subsystems could be inhibited (e.g., Somerville 2002; Benson et al. 2002b). It is possible that the observed satellites are in fact embedded in much larger, more massive dark subhalos (Stoehr et al. 2002), or originally formed in more massive subhalos that were later tidally stripped (Kravtsov et al. 2004), and that we are therefore observationally sampling a less populous region of the initial satellite mass function.

All of these solutions aim to resolve the discrepancy between theory and observation by creating models that predict fewer directly observable satellites. A complementary observational approach would be to place more stringent constraints on the faint end of the galaxy luminosity function, but attempts to do so are hampered by the low surface brightnesses expected of galaxies in that regime. The advent of wide-field CCD surveys such as the Sloan Digital Sky Survey (SDSS; York et al. 2000) has made it possible to detect stellar structures with extremely low surface brightnesses (see, e.g., Willman et al. 2002), and in 2004 and 2005 data from SDSS were used to find two new Local Group members, Andromeda IX (And IX; Zucker et al. 2004b) and Ursa Major (Willman et al. 2005), satellites of M31 and the Milky Way, respectively; at the time of its discovery, each of these two objects was determined to be the least luminous, lowest surface brightness galaxy found up to that point.

Since the discovery of And IX, we have been using SDSS photometry of M31 and its surroundings to identify possible M31 companions for deeper observations on other telescopes. In this Letter, we report the discovery, using SDSS and follow-up photometric data, of a new dwarf spheroidal companion to M31, one comparable in luminosity to And IX. Keck spectroscopy of stars in the field of this new satellite, and the kinematic and abundance information derived therefrom, will be presented in a companion paper (P. Guhathakurta et al. 2007, in preparation). For this work, we have assumed a distance to M31 of 783 kpc [$(m - M)_0 = 24.47$; e.g., Holland 1998; Stanek & Garnavich 1998].

## 2. OBSERVATIONS AND DATA ANALYSIS

SDSS imaging data are obtained in five bandpasses (*u*, *g*, *r*, *i*, and *z*; Fukugita et al. 1996; Gunn et al. 1998; Hogg et al. 2001; Gunn et al. 2006) and are processed with automated pipelines to measure photometric and astrometric properties (Lupton et al. 1999; Stoughton et al. 2002; Smith et al. 2002; Pier et al. 2003; Ivezić et al. 2004; Lupton 2007; Tucker et al. 2006). The data used in this work were taken on 2002 October 5 and span $\sim 18° \times 2.5°$ along M31's major axis (for details, see Zucker et al. 2004a). For dereddening and conversion from SDSS (AB) to *V*, *I* (Vega) magnitudes, we use Schlegel et al. (1998) and Smith et al. (2002), respectively.

By selecting stars in the SDSS M31 scan with colors and magnitudes characteristic of red giant branch (RGB) stars at

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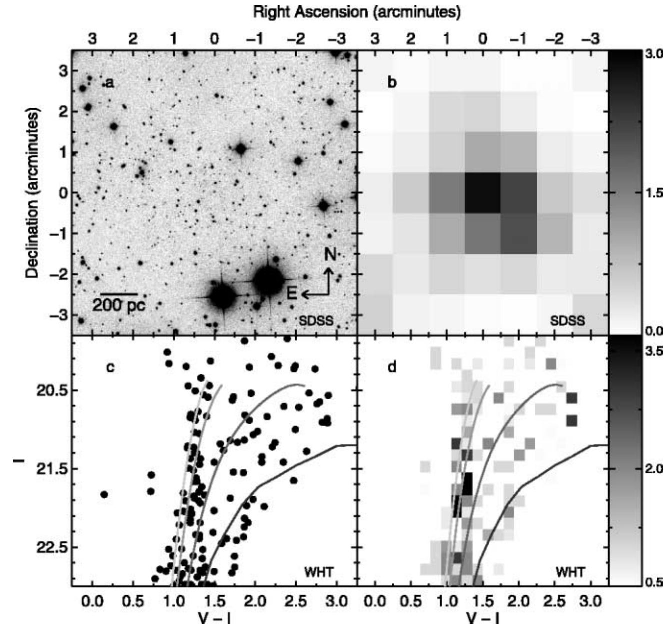


FIG. 1.—Andromeda X as seen by SDSS and WHT: (*a*) Sum of SDSS *g*, *r*, and *i* images centered on And X. (*b*) Spatial density of presumed SDSS "blue" red giant stars in the same area, binned 1′ × 1′ and smoothed with a 1.5′ FWHM Gaussian. The gray-scale bar to the right indicates the significance of the spatial overdensity, in units of the background standard deviation. (*c*) Dereddened WHT CMD of stars within 2′ of the center of And X, with fiducial sequences overplotted for Galactic globular clusters with metallicities of (*left to right*) [Fe/H] = −2.2 (M15), −1.6 (M2), −0.7 (47 Tuc), and −0.3 (NGC 6553) (Da Costa & Armandroff 1990; Sagar et al. 1999), shifted to a distance modulus of 24.47. (*d*) Dereddened WHT Hess diagram of stars within 2′ of the center of And X, minus the area-scaled Hess diagram of a control field. The data are binned by 0.15 mag in $(V - I)$ and $I$. The gray-scale bar indicates the number of stars in each bin. Overplotted fiducials are as for (*c*).

the distance of M31, we discovered And IX, a new dwarf spheroidal satellite of M31 (Zucker et al. 2004b). Owing to their low metallicity (Harbeck et al. 2005), the RGB stars in And IX are relatively blue; limiting our photometric criteria to select *blue* RGB stars at the distance of M31, a large number of additional, less prominent overdensities were revealed. It is important to note that these stellar overdensities are not directly visible in SDSS images (see, e.g., Fig. 1*a*) and are only detected as enhancements of the spatial density of stars within a specific color-magnitude bin (Fig. 1*b*); in SDSS data, such enhancements may consist of a few stars spread across several square arcminutes. Deeper follow-up observations are therefore required in order to determine the nature of these overdensities, in particular to ascertain if they represent new M31 satellites.

In the autumn of 2004, we used the 4.2 m William Herschel Telescope (WHT) and 2.5 m Nordic Optical Telescope (NOT) on La Palma to image targets selected from these SDSS stellar overdensities. We observed at the WHT on 2004 September 14 and 15, using the Prime Focus Imaging Camera with Harris *VI* filters. Unfortunately, we were only able to obtain short integrations of one of the satellite candidates under suitable observing conditions (seeing $\lesssim 1.5''$). The WHT images were reduced with standard IRAF tasks, and DAOPHOT II/ALLSTAR (Stetson 1994) was used to obtain $V$ and $I$ photometry, which we bootstrap-calibrated with SDSS data. Figure 1*c* shows the resulting dereddened $(I, V - I)$ color-magnitude diagram (CMD), for stars in a circular 2′ radius region centered on the location of the satellite candidate. Despite significant field contamination, an RGB is visible. Subtracting the area-scaled CMD of an outer control region yields the Hess diagram in Figure 1*d*. The narrowness, shape, and color of the RGB indicate the presence of a spatially distinct, presumably metal-poor ([Fe/H] $\lesssim -1.6$) stellar population at roughly the distance of M31 (the tip of the RGB [TRGB] appears to be at $I \sim 20.2 \pm 0.2$), similar to that of And IX (Zucker et al. 2004b; Harbeck et al. 2005). (It should be noted that the blueness of the RGB is not an unambiguous indicator of low metallicity and could also be due to the presence of a relatively young stellar population.) The additional similarities between the observed candidate and And IX, with regard to low surface brightness and small size, are further indications that the object is a new dwarf spheroidal (dSph) satellite of M31; we have therefore given it the name Andromeda X (And X).

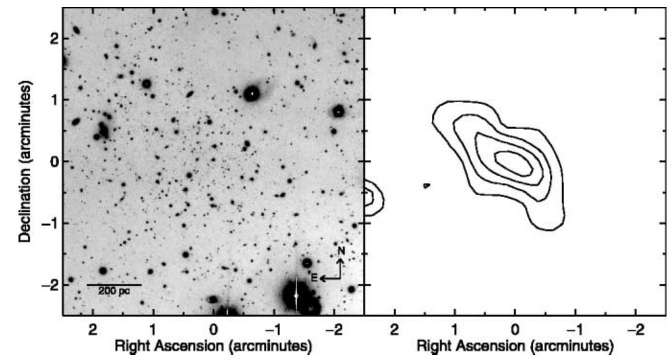


FIG. 2.—And X as seen by the NOT. *Left*: Summed *g*, *r*, and *i* images centered on And X. *Right*: Contour plot showing the spatial distribution of stars within the RGB locus of And X. The data have been binned 15″ × 15″, and the contours shown are 3.5, 4.5, 5.5, and 6.5 $\sigma$ above the background level.

During our subsequent run at the NOT (2004 October 6–11), we used the Mosaic Camera (MOSCA) and SDSS *gri* filters to obtain deeper imaging of this candidate with excellent seeing (typically 0.6″–0.9″). We used the same reduction and analysis tasks to obtain SDSS-calibrated *gri* photometry. The left panel of Figure 2 shows the co-addition of the NOT *g*, *r*, and *i* imaging data, in which And X is revealed as an elliptical stellar overdensity (oriented roughly northeast-southwest) at the center; the overdensity is seen more clearly in the contour plot to the right. The superior depth and resolution of the NOT data are evident in the resulting CMDs of the central 2′ radius region (Figs. 3*a* and 3*d*), in which And X's narrow, blue RGB clearly stands out. The background-subtracted dereddened Hess diagrams (Figs. 3*c* and 3*f*) are overplotted with the dereddened SDSS CMD of NGC 2419, a Galactic globular cluster ([Fe/H] = −2.12), shifted to a distance modulus of 24.24 (see § 3); given the uncertainties in both And X's distance and reddening, the agreement between And X and NGC 2419 is remarkable, even hinting at the possible presence of blue horizontal-branch stars in the $(g, g - r)$ CMD, and provides further evidence of And X's low metallicity ([Fe/H] $\sim -2$).

## 3. PROPERTIES OF AND X

Using background-subtracted photometric data from the NOT observations, we constructed a spatial density map of probable And X members in radial bins of 15″, to which we fit two-dimensional King (1966) and Sérsic (1968) profiles. We then applied the techniques of Kniazev et al. (2004) to the *g*, *r*, and *i* images, masking foreground stars and subtracting a fitted sky level, binning the resulting data in circular annuli to measure the central surface brightness and total magnitude in each filter. No unresolved luminous component was detected, so we used the method of Zucker et al. (2004a) to estimate the

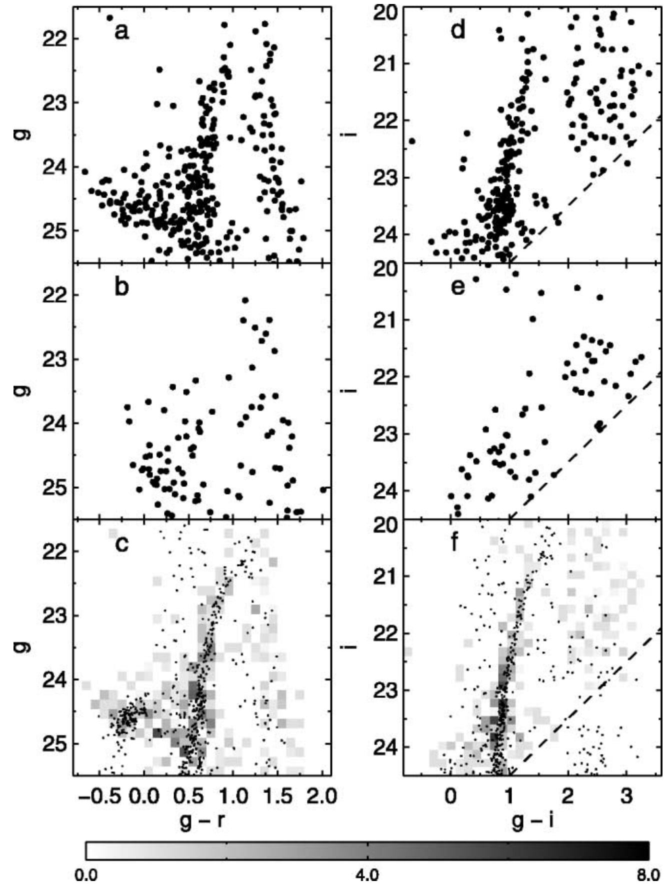


FIG. 3.—Dereddened And X photometry from NOT data: (*a*) ($g$, $g-r$) CMD of stars within 2′ of the center of And X. (*b*) ($g$, $g-r$) CMD of stars from an outer annulus of equal area. (*c*) ($g$, $g-r$) Hess diagram of stars within 2′ of the center of And X, minus the area-scaled Hess diagram of a larger control region. The data are binned by 0.15 mag in $g$ and ($g-r$). The SDSS CMD of an inner annulus of NGC 2419 (a Galactic globular cluster; [Fe/H] = −2.12), dereddened and shifted to a distance modulus of 24.24 (see § 3), is overplotted as dots. (*d*) ($i$, $g-i$) CMD of stars within 2′ of the center of And X. (*e*) ($i$, $g-i$) CMD of stars from the outer annulus of equal area. (*f*) ($i$, $g-i$) Hess diagram of the central region, minus the scaled control region, binned by 0.15 mag in $i$ and 0.10 mag in ($g-i$). The CMD of NGC 2419 is overplotted, as in (*c*). The dashed line in (*d*)–(*f*) shows the approximate detection limit of our data; the gray-scale bar indicates the number of stars per bin in (*c*) and (*f*).

total surface brightness and luminosity by comparison with SDSS observations of the Pegasus dIrr; comparison to the luminosity function of the Draco dSph (Odenkirchen et al. 2001) confirms that these estimates are reasonable for a range of stellar populations (Zucker et al. 2004a). The undereddened central surface brightnesses derived for And X in this way are 27.6 ± 0.4, 26.7 ± 0.3, and 26.3 ± 0.3 mag in $g$, $r$, and $i$, respectively (27.1 ± 0.5 mag in $V$); the measured total magnitudes in $g$, $r$, and $i$ are 17.1 ± 0.4, 16.1 ± 0.3, and 15.8 ± 0.3 mag (16.5 ± 0.5 mag in $V$). Table 1 lists the derived structural parameters and dereddened $V$-band magnitudes for And IX and And X.

Determining a more precise distance to And X with the data in hand is problematic, due to the sparseness of And X's CMD in the region of the TRGB. We closely examined the field-star–subtracted $I$-band stellar luminosity functions derived from both WHT and NOT data within the central 2′ radius of And X; however, even convolution with an edge detection kernel did not yield an unambiguous TRGB magnitude, with the measured $I_{\rm TRGB}$ ranging from approximately 20.14 to 20.36, after correction for a foreground reddening of $A_I = 0.24$. Assuming a metallicity of

TABLE 1
PROPERTIES OF AND IX AND AND X

| Parameter[a] | And IX | And X |
|---|---|---|
| R.A. (J2000.0) ........... | 00 52 52.8 | 01 06 33.7 |
| Decl. (J2000.0) .......... | +43 12 00 | +44 48 15.8 |
| King $r_c$ (arcmin) .......... | 1.35[b] | 1.33 |
| King $r_t$ (arcmin) .......... | 5.9[b] | 7.2 |
| Sérsic $n$ .................. | 1.6[b] | 1.2 |
| Sérsic $r_h$ (arcmin) ........ | 1.43[b] | 1.63 |
| Axial ratio ($b/a$) .......... | 0.75 | 0.56 |
| Position angle (deg) ...... | 80 | 60 |
| $A_V$ (mag) ................. | 0.26 | 0.41 |
| $\mu_{0,V}$ (mag) ............... | 26.77 ± 0.09 | 26.7 ± 0.5 |
| $V_{\rm tot}$ (mag) ................ | 16.17 ± 0.06 | 16.1 ± 0.5 |
| $(m-M)_0$ (mag) .......... | 24.48 ± 0.20 | 24.12–24.34 ± 0.10 |
| $M_{{\rm tot},V}$ (mag) .............. | −8.3 | −8.1 |

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
[a] Surface brightnesses and integrated magnitudes are corrected for the mean Galactic foreground reddenings, $A_V$, shown. Unless otherwise noted, values for And IX are from Zucker et al. (2004b).
[b] From Harbeck et al. (2005).

[Fe/H] = −2.2 and a TRGB color of $(V-I)_{\rm TRGB} = 1.2$ (as for And IX; Zucker et al. 2004b), from the calibration of Da Costa & Armandroff (1990) we obtain the relation $(m-M)_0 = I_{\rm TRGB} + 3.98$, yielding a distance modulus range of $(m-M)_0 \sim$ 24.12–24.34, with uncertainties on the order of 0.1 mag (667–738 kpc, ±30–35 kpc). At an M31 distance of 783 kpc, the angular separation of And X from the center of M31, ~5.5°, gives a projected separation of 75 kpc; considering the above range of And X distance estimates puts And X at 87–138 kpc from the center of M31, well within M31's estimated virial radius (e.g., Benson et al. 2002b). Thus, And X is in all likelihood a bound satellite of M31, with a dereddened integrated magnitude of $V_{\rm tot} \sim 16.1$, translating to an absolute magnitude of $M_V \sim -8.1 \pm 0.5$ mag.

## 4. DISCUSSION

As shown in Table 1, And X is comparable in size, surface brightness, and apparent magnitude to And IX, and, despite the uncertainty in its distance, And X appears to be somewhat lower in luminosity ($M_V \sim -8.1$). We conclude that And X is a new extremely faint dSph companion of M31, a result confirmed by kinematic data (P. Guhathakurta et al. 2007, in preparation). The earlier discovery of And IX raised the question of whether such low-luminosity galaxies were a rarity in the Local Group or whether And IX was the tip of an iceberg, one of a large population of faint satellites that have thus far remained undetected. And X's discovery, along with the recent discoveries of numerous other faint dwarfs around the Milky Way and M31 (Willman et al. 2005; Zucker et al. 2006a, 2006b; Belokurov et al. 2006, 2007; Martin et al. 2006), suggests that the latter scenario is closer to the truth—that M31 and the Milky Way have a large number of low-luminosity satellites.

Further analysis of SDSS data is therefore likely to yield more such dwarfs. To test this scenario, we are following up other stellar overdensities in the SDSS M31 scan with deeper observations on other telescopes. Intriguingly, in projection And IX and And X lie relatively close to each other and to the major axis of M31, northeast of M31's center (Fig. 4); as more new M31 satellites are found (as now appears likely), we will be able to place constraints on the spatial distribution of M31 satellites and their (an)isotropy (e.g., Koch & Grebel 2006; McConnachie & Irwin 2006), as well as on the satellite luminosity function.

Thus, the discovery and characterization of extremely low luminosity galaxies like And IX and And X play a critical role in reconciling the predictions of current CDM galaxy formation models with the observable local universe.

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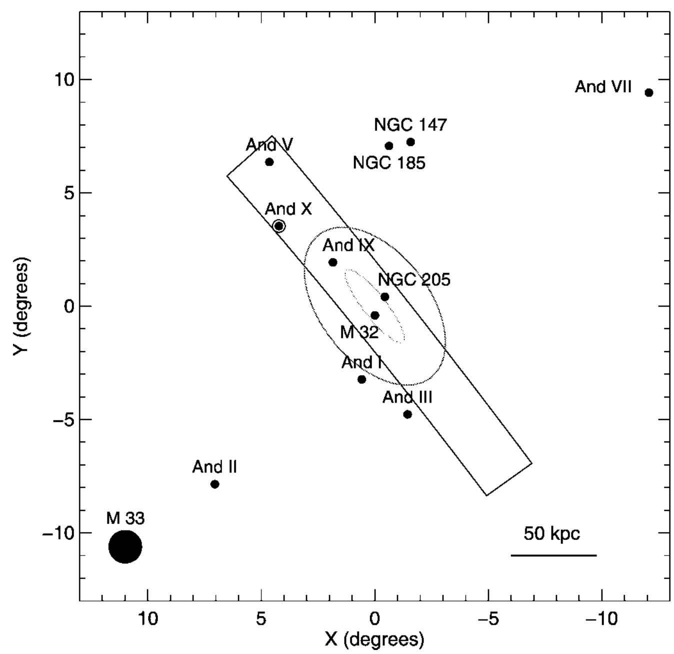


FIG. 4.—Projected distribution of M31's nearest satellites (after Ferguson et al. 2002), with the addition of And IX and And X. The inner ellipse indicates the rough optical size of M31's disk, and the outer ellipse the approximate extent of the INT survey (see, e.g., Ferguson et al. 2002). The coverage of the SDSS M31 scan is shown by the long stripe along the major axis of M31.

## REFERENCES

Belokurov, V., et al. 2006, ApJ, 647, L111
Belokurov, V., et al. 2007, ApJ, 654, 897
Benson, A. J., Frenk, C. S., Lacey, C. G., Baugh, C. M., & Cole, S. 2002a, MNRAS, 333, 177
Benson, A. J., Lacey, C. G., Baugh, C. M., Cole, S., & Frenk, C. S. 2002b, MNRAS, 333, 156
Da Costa, G. S., & Armandroff, T. E. 1990, AJ, 100, 162
Ferguson, A. M. N., Irwin, M. J., Ibata, R. A., Lewis, G. F., & Tanvir, N. R. 2002, AJ, 124, 1452
Fukugita, M., Ichikawa, T., Gunn, J. E., Doi, M., Shimasaku, K., & Schneider, D. P. 1996, AJ, 111, 1748
Gunn, J. E., et al. 1998, AJ, 116, 3040
Gunn, J. E., et al. 2006, AJ, 131, 2332
Harbeck, D., Gallagher, J., Grebel, E., Koch, A., & Zucker, D. 2005, ApJ, 623, 159
Hogg, D. W., Finkbeiner, D. P., Schlegel, D. J., & Gunn, J. E. 2001, AJ, 122, 2129
Holland, S. 1998, AJ, 115, 1916
Ivezić, Ž. et al. 2004, Astron. Nachr., 325, 583
King, I. R. 1966, AJ, 71, 64
Kniazev, A. Y., Grebel, E. K., Pustilnik, S. A., Pramskij, A. G., Kniazeva, T. F., Prada, F., & Harbeck, D. 2004, AJ, 127, 704
Klypin, A., Kravtsov, A. V., Valenzuela, O., & Prada, F. 1999, ApJ, 522, 82
Koch, A., & Grebel, E. 2006, AJ, 131, 1405
Kravtsov, A., Gnedin, O., & Klypin, A. 2004, ApJ, 609, 482
Lupton, R. H. 2007, AJ, submitted
Lupton, R., Gunn, J., & Szalay, A. 1999, AJ, 118, 1406
Martin, N. F., Ibata, R. A., Irwin, M. J., Chapman, S., Lewis, G. F., Ferguson, A. M. N., Tanvir, N., & McConnachie, A. W. 2006, MNRAS, 371, 1983
McConnachie, A. W., & Irwin, M. J. 2006, MNRAS, 365, 902
Moore, B., Ghigna, S., Governato, F., Lake, G., Quinn, T., Stadel, J., & Tozzi, P. 1999, ApJ, 524, L19
Odenkirchen, M., et al. 2001, AJ, 122, 2538
Pier, J. R., Munn, J. A., Hindsley, R. B., Hennessy, G. S., Kent, S. M., Lupton, R. H., & Ivezić, Ž. 2003, AJ, 125, 1559
Sagar, R., Subramaniam, A., Richtler, T., & Grebel, E. K. 1999, A&AS, 135, 391
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Sérsic, J. 1968, Atlas de Galaxias Australes (Córdova: Obs. Astron.)
Smith, J. A., et al. 2002, AJ, 123, 2121
Somerville, R. S. 2002, ApJ, 572, L23
Stanek, K., & Garnavich, P. 1998, ApJ, 503, L131
Stetson, P. B. 1994, PASP, 106, 250
Stoehr, F., White, S. D. M., Tormen, G., & Springel, V. 2002, MNRAS, 335, L84
Stoughton, C., et al. 2002, AJ, 123, 485
Tucker, D., et al. 2006, Astron. Nachr., 327, 821
Willman, B., Dalcanton, J., Ivezić, Ž., Jackson, T., Lupton, R., Brinkmann, J., Hennessy, G., & Hindsley, R. 2002, AJ, 123, 848
Willman, B., et al. 2005, ApJ, 626, L85
York, D. G., et al. 2000, AJ, 120, 1579
Zucker, D. B., et al. 2004a, ApJ, 612, L117
———. 2004b, ApJ, 612, L121
———. 2006a, ApJ, 643, L103
———. 2006b, ApJ, 650, L41