

## ANDROMEDA XXVIII: A DWARF GALAXY MORE THAN 350 kpc FROM ANDROMEDA

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### ABSTRACT

We report the discovery of a new dwarf galaxy, Andromeda XXVIII, using data from the recently released Sloan Digital Sky Survey Data Release 8. The galaxy is a likely satellite of Andromeda, and, at a separation of  $365_{-1}^{+17}$  kpc, would be one of the most distant of Andromeda’s satellites. Its heliocentric distance is  $650_{-80}^{+150}$  kpc, and analysis of its structure and luminosity shows that it has an absolute magnitude of  $M_V = -8.5_{-1.0}^{+0.4}$  and half-light radius of  $r_h = 210_{-50}^{+60}$  pc, similar to many other faint Local Group dwarfs. With presently available imaging we are unable to determine whether there is ongoing or recent star formation, which prevents us from classifying it as a dwarf spheroidal or a dwarf irregular.

*Key words:* galaxies: dwarf – galaxies: individual (And XXVIII) – Local Group

*Online-only material:* color figure

### 1. INTRODUCTION

In recent years, the environment of Andromeda has been a prime location for the discovery of dwarf galaxies and tidal structures, much of which has been enabled by large surveys on the Isaac Newton Telescope (Ferguson et al. 2002; Irwin et al. 2008) and the Canada–France–Hawaii telescope (Ibata et al. 2007; McConnachie et al. 2009; Martin et al. 2006, 2009). These surveys have obtained deep observations over a significant fraction of the area within 180 kpc of Andromeda and yielded a considerable number of new discoveries. In addition to these dedicated surveys, two satellites of Andromeda have been found in the Sloan Digital Sky Survey (SDSS) imaging (And IX and X; Zucker et al. 2004, 2007), using an early SDSS scan targeting Andromeda specifically. More recently, the SDSS project has released Data Release 8 (Aihara et al. 2011), which adds  $\sim 2500$  deg<sup>2</sup> of imaging coverage in the south Galactic cap and covers almost half of the area within 35° of Andromeda. While SDSS is substantially shallower than the dedicated M31 surveys, it is deep enough to enable the discovery of relatively bright (by today’s standards) dwarf galaxies.

It is in this new SDSS coverage that we report the discovery of a dwarf galaxy, which we are preliminarily calling Andromeda XXVIII (And XXVIII). The dwarf is separated from Andromeda by 27:7 on the sky, which gives it a minimum distance to M31 of 365 kpc. This distance is significantly larger than the virial radius of Andromeda ( $r_{\text{vir}} = 300$  kpc; Klypin et al. 2002). And XXVIII is therefore one of a handful of known examples of dwarf galaxies that are less likely to be significantly influenced by the environment of their host galaxy, which makes them important test cases for theories of dwarf galaxy formation and evolution.

### 2. DETECTION

At the distance of Andromeda ( $785 \pm 25$  kpc; McConnachie et al. 2005), searches for dwarf galaxies in the SDSS are limited to using red giant branch (RGB) stars as tracers of the underlying population of main-sequence and subgiant stars. Alternative tracers commonly used for detecting dwarf galaxies around the Milky Way, such as horizontal branch or main-sequence turnoff

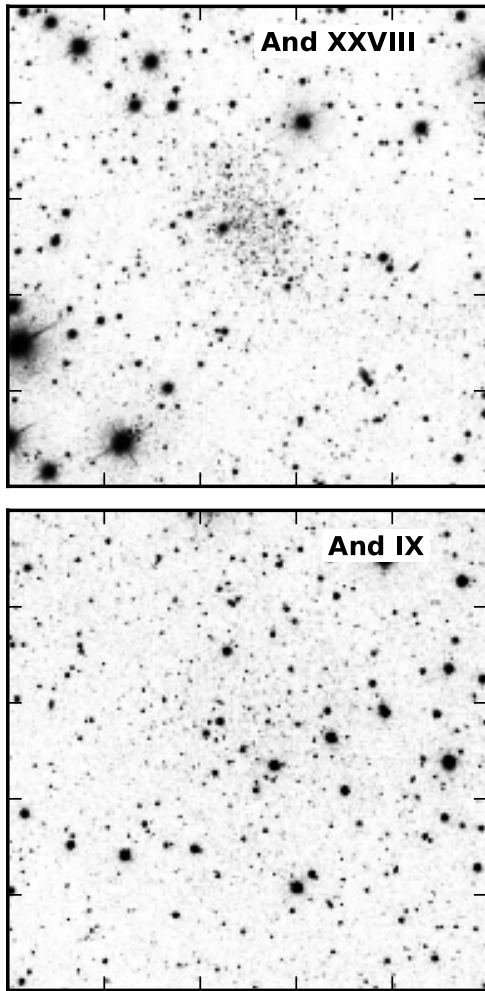
stars, are much too faint to be detected. To detect dwarf galaxies in SDSS we compute star counts in  $2' \times 2'$  bins, selecting only stars with  $0.3 < r - i < 0.8$ , colors roughly similar to metal-poor giant branch stars. Overdensities are readily apparent upon visual inspection of the resulting map as “hot pixels,” typically with counts of 10–15 objects as compared to the background of 1–3 objects per bin. Most of these overdensities are galaxy clusters at intermediate redshift, which contain many spatially unresolved member galaxies that are erroneously classified as stars and have similar colors as giant branch stars. Visual inspection of the SDSS image along with the color–magnitude diagram (CMD) is sufficient to reject these false positives.

The SDSS image of And XXVIII is shown in Figure 1, along with an image of And IX for comparison, and the properties of And XXVIII are summarized in Table 1. The CMD of the dwarf is shown in Figure 2, along with a CMD of the field region surrounding the dwarf, a plot of measured star positions, and a histogram as a function of  $i$ -band magnitude. These plots are also shown for And IX, another dwarf galaxy that was discovered in SDSS. An isochrone from Dotter et al. (2008) of an old, metal-poor system (12 Gyr old,  $[\text{Fe}/\text{H}] = -2.0$ ) is also shown on the CMD to illustrate the position of the RGB. An overdensity at  $0.3 < (r - i)_0 < 0.8$  is clearly visible. The RGB is very wide in color, owing to considerable photometric uncertainty at very faint magnitudes in SDSS, which is illustrated by the error bar on the left side of the CMD (estimated from repeat imaging of SDSS stripe 82; Bramich et al. 2008).

### 3. PROPERTIES OF AND XXVIII

We computed the distance to And XXVIII by measuring the magnitude of the tip of the red giant branch (TRGB), which has a roughly constant absolute magnitude in metal-poor stellar systems (Bellazzini et al. 2001). This method has been used extensively for dwarf galaxies (e.g., McConnachie et al. 2005; Martin et al. 2009), since the TRGB is often the only distinguishable feature in the CMD of distant systems.

Quantitatively measuring the position of the TRGB is more complicated than it would appear from looking at the CMD. This is especially true in dwarf galaxies, where the giant branch is sparsely populated and the small number counts



**Figure 1.** SDSS image of And XXVIII (top), and, for comparison, an SDSS image of And IX (bottom), which was also discovered in SDSS (Zucker et al. 2004). Both images were obtained from the SDSS SkyServer and are  $6'6 \times 6'6$ . North is up and east is to the left.

**Table 1**  
Properties of And XXVIII

Parameter	Value
$\alpha$ (J2000)	$22^{\text{h}}32^{\text{m}}41^{\text{s}}.2$
$\delta$ (J2000)	$31^{\circ}12'58''.2$
$E(B - V)$	$0.087^{\text{a}}$
Ellipticity	$0.34 \pm 0.13$
Position angle (N to E)	$39^{\circ} \pm 16$
$r_h$	$1'.11 \pm 0'.21$
$r_h$	$210^{+60}_{-50}$ pc
$D$	$650^{+150}_{-80}$ kpc
$(m-M)_0$	$24.1^{+0.5}_{-0.2}$
$r_{\text{M31}}$	$365^{+17}_{-1}$ kpc <sup>b</sup>
$M_V$	$-8.5^{+0.4}_{-1.0}$

**Notes.**

<sup>a</sup> Schlegel et al. (1998).

<sup>b</sup> Since the measured distance puts And XXVIII very close to the tangent point along its line of sight, the uncertainty in  $r_{\text{M31}}$  is very asymmetric.

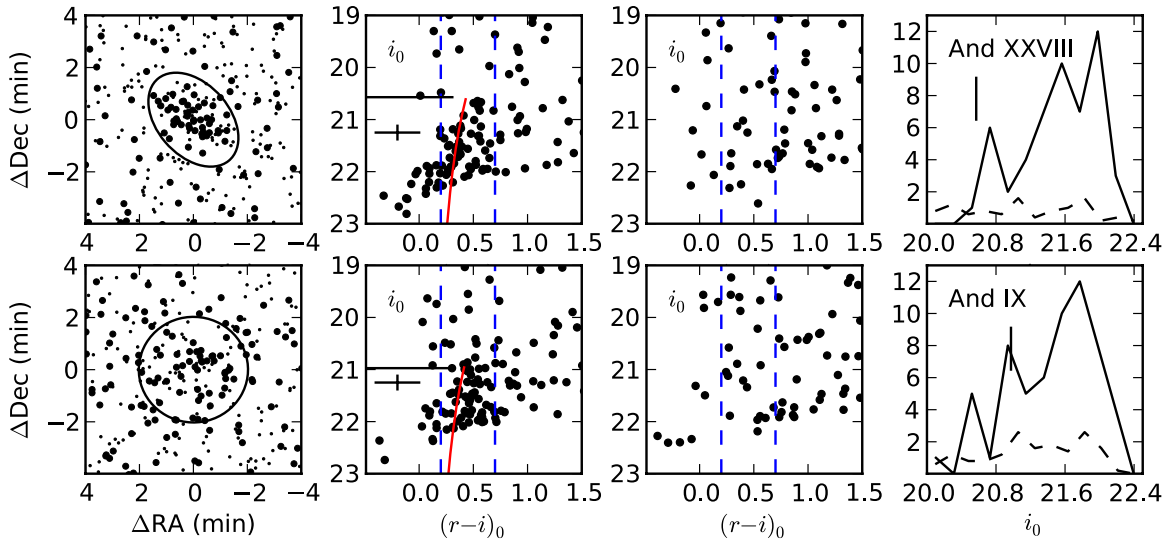
(2006), which modeled the TRGB luminosity function as

$$\psi = \begin{cases} 10^{a(m-m_{\text{TRGB}})+b} & m - m_{\text{TRGB}} \geq 0, \\ 10^{c(m-m_{\text{TRGB}})} & m - m_{\text{TRGB}} < 0. \end{cases} \quad (1)$$

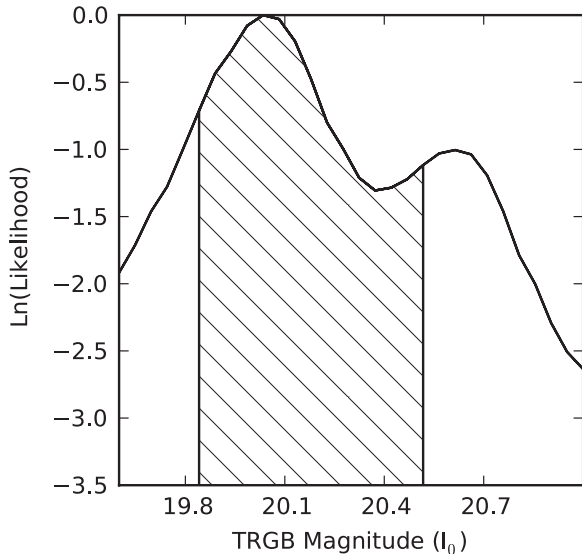
This broken power-law form takes three parameters:  $a$  and  $c$  are the slopes of the luminosity function fainter and brighter than the TRGB, while  $b$  is the strength of the transition at the TRGB. We adopted the values from Makarov et al. (2006) of  $a = 0.3$  and  $c = 0.2$ , and  $b = 0.6$ . For the TRGB fit, we selected stars in our RGB color cuts with magnitudes  $19.5 < i < 21.7$  to avoid incompleteness at faint magnitudes. Though the data at the faintest magnitudes are not critical for finding the position of breaks in the luminosity function that might correspond to the TRGB, the faint end of the luminosity function does affect our ability to determine the statistical significance of a measured TRGB position. As a result, we try to use as deep of data as possible without reaching significant photometric incompleteness. The SDSS photometry was converted to Johnson  $I$  band using the prescriptions of Jordi et al. (2006), and an intrinsic  $I$ -band magnitude of the TRGB was assumed of  $-4.04 \pm 0.12$  (Bellazzini et al. 2001). The likelihood function of the model as a function of TRGB position is shown in Figure 3. We find that the likelihood is maximized at  $m_{I,\text{TRGB}} = 20.1$ , but a second peak also appears at  $m_{I,\text{TRGB}} = 20.6$  (in the Gunn- $i$  filter, 20.6 and 21.1, respectively). This is the result of a clump of stars slightly fainter than  $m_I = 20.1$ , which causes the TRGB magnitude to change significantly depending on whether or not they are included as part of the RGB. Though the fainter peak cannot be ruled out, the TRGB magnitude we quote of  $m_{I,\text{TRGB}} = 20.1^{+0.5}_{-0.1}$  is the center of the more likely peak. The uncertainty on this TRGB value is the 67% confidence interval, which was computed by creating a cumulative probability distribution function and measuring the 16.5%–83.5% region. The resulting uncertainties are asymmetric, and this asymmetry will propagate into all derived quantities, but this is a natural result of the bimodal likelihood function. The measured TRGB position yields a distance modulus of  $24.1^{+0.5}_{-0.2}$ , which places the dwarf at a heliocentric distance of  $650^{+150}_{-80}$  kpc. Because this is very similar to the point of closest approach to Andromeda along this line of sight (the “tangent point”), the distance between And XXVIII and M31 is largely insensitive to errors in the heliocentric distance and is measured to be  $r_{\text{M31}} = 365^{+17}_{-1}$  kpc.

To measure the luminosity of And XXVIII, we computed luminosity functions from SDSS data for three similar dwarf galaxies with known distances and luminosities (And III,  $M_V = -9.87 \pm 0.3$ , McConnachie & Irwin 2006; And V,  $M_V = -9.22 \pm 0.3$ , McConnachie & Irwin 2006; And X,  $M_V = -8.13 \pm 0.5$ , Zucker et al. 2007). We scaled these galaxies to a fiducial luminosity and distance by correcting the dereddened apparent magnitude of each galaxy’s stars for their respective distances and by scaling the number of stars in each luminosity bin by the total luminosity of the galaxy. We then took the mean of these profiles to produce a composite luminosity function that was less affected by the “shot noise” inherent in such low number count systems. Since our comparison objects span a range of distances, we applied a faint-magnitude cut to ensure that the luminosity function of even the most distant comparison dwarf was still photometrically complete. For stars with colors typical of RGB stars, we find that the data are complete to approximately  $i = 21.7$  (non-dereddened). Since the most distant comparison dwarf has a distance modulus that is greater

lead to significant “shot noise” (Martin et al. 2008). We used the maximum-likelihood estimator described in Makarov et al.



**Figure 2.** Detection plots for And XXVIII (top row) with the same plots for And IX shown for comparison ( $M_V \sim -8.3$ , bottom row). Far left: the position of stars detected in SDSS is plotted, with stars that fall within our color cut as large points, and other stars as small points. An ellipse at 1.5 times the half-light radius is also shown. Middle left: color-magnitude diagram of stars inside twice the half-light radius. The color cut used to detect RGB stars is shown by the dashed vertical lines. An isochrone from Dotter et al. (2008) is overlotted ( $[\text{Fe}/\text{H}] = -2.0$  for And XXVIII,  $[\text{Fe}/\text{H}] = -2.2$  for And IX), along with a horizontal line indicating the tip of the red giant branch, and a representative photometric error bar on the left. Middle right: color-magnitude diagram of a background annulus. Far right: luminosity function of the color-selected red giant stars (solid line) and the background annulus (dashed). (A color version of this figure is available in the online journal.)



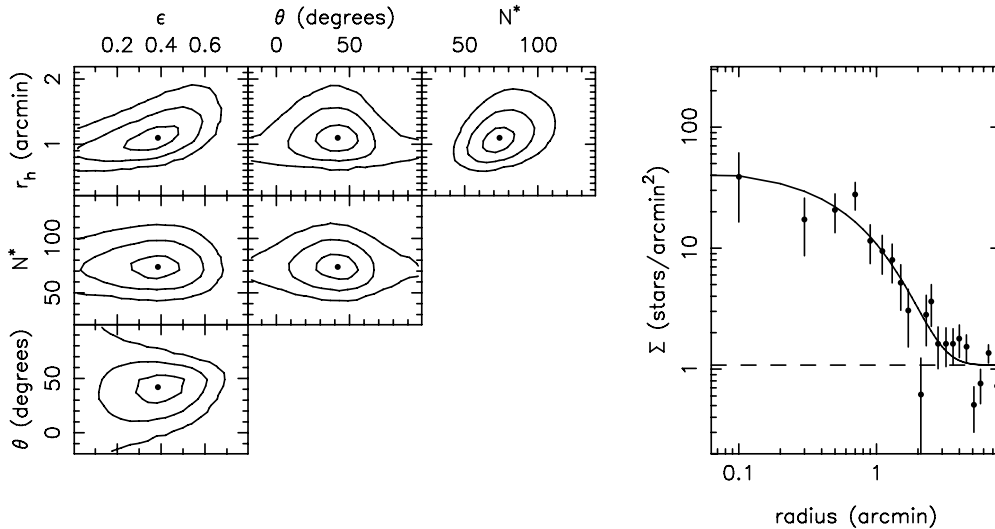
**Figure 3.** Likelihood function of the TRGB position of And XXVIII, arbitrarily normalized. The hatched region is the 67% confidence interval. The secondary maximum is clearly visible and less significant than the primary peak, but cannot be ruled out.

than that of And XXVIII by 0.4, our corresponding completeness cut on And XXVIII for the luminosity function comparison was  $i = 21.3$  ( $i_0 = 21.5$ ). This binned, composite luminosity function was then scaled to match that of And XXVIII (again using a maximum-likelihood method to properly account for Poissonian uncertainties, and with uncertainties on the comparison dwarfs' luminosities included), and the scaling factor thus determined the luminosity of the galaxy relative to the fiducial luminosity. This method produces results largely equivalent to the method of Martin et al. (2008) for relatively bright dwarfs. The luminosity determined by this method is  $M_V = -8.5^{+0.4}_{-1.0}$  (the large uncertainty is primarily due to the uncertainty in the distance measurement), which is generally similar to that of

other local group dwarfs. To ensure that issues of photometric completeness or other systematics did not bias our composite luminosity function, we also constructed a luminosity function from deep observations of the Draco dwarf (obtained on the Canada-France-Hawaii Telescope; Ségal et al. 2007) and used the same scaling method to measure the luminosity of And XXVIII, which resulted in an identical value. As a final check, we compared And XXVIII to the model luminosity functions of Dotter et al. (2008) and again obtained a luminosity that is in good agreement with the other methods ( $M_V = -8.32$ ).

The considerable scatter in color of the RGB stars due to photometric error makes it difficult to determine the metallicity of the galaxy. This uncertainty is illustrated by the CMD of And IX (Figure 2, bottom middle left), which was measured by Collins et al. (2010) with deep imaging to have  $[\text{Fe}/\text{H}] = -2.2 \pm 0.2$ . Though the fit to the Dotter isochrone is very good in the Collins et al. (2010) data, the SDSS data show significant scatter in color and appear to be systematically offset in color from the isochrone. It is unclear whether this is the result of inaccuracies in the isochrone or calibration error at very faint magnitudes in the SDSS, but because of these uncertainties, it is not possible to constrain the metallicity of the galaxy with the observations available. We nevertheless can say that the CMD of And XXVIII is not obviously dissimilar to other metal-poor dwarf galaxies.

We computed the radial profile of And XXVIII, along with the position, half-light radius, eccentricity, and position angle using the maximum-likelihood technique described by Martin et al. (2008). This method assumes an exponential profile for the dwarf galaxy and a constant background level. Figure 4 shows on the left maximum-likelihood contours of the half-light radius, ellipticity ( $\epsilon$ ), position angle ( $\theta$ ), and number of detected stars in the overdensity within the SDSS data ( $N_*$ ), while the right side shows the radial profile fit. The structural parameters have one-dimensional  $1\sigma$ ,  $2\sigma$ , and  $3\sigma$  confidence areas overlaid. And XXVIII is well populated enough, even in the relatively shallow SDSS data, to permit easy determination



**Figure 4.** Left: confidence areas for the measurement of half-light radius, ellipticity, position angle, and number of detected stars. The contours correspond, when projected on the axes, to  $1\sigma$ ,  $2\sigma$ , and  $3\sigma$  uncertainties (to allow reading of the marginalized  $1\sigma$  value straight from the plot for each parameter). The filled circles correspond to the peak of the maximum-likelihood function. Right: radial profile of And XXVIII, where stars have been binned according to the best-fit structural parameters with Poisson uncertainties on each bin. The solid black line is the best-fit exponential profile, while the dashed horizontal line is the measured background level.

of these parameters without large uncertainties. The fact that  $N_* = 0$  is excluded at  $\gg 3\sigma$  provides a quantitative indication that this overdensity is unlikely to be a statistical artifact. The fact that the half-light radius is well determined also gives us confidence that the overdensity is real, since the fitting procedure usually finds unreasonably large values for  $r_h$  when run on non-galaxies. The half-light radius of  $r_h = 210_{-50}^{+60}$  pc is typical of other Local Group dwarf galaxies and is roughly the size of Draco. The position angle has a considerable uncertainty associated with it, along with some covariance with ellipticity. These factors may make the ellipse in the top left panel of Figure 2 appear slightly misaligned when judging the fit by eye.

#### 4. DISCUSSION

Throughout this work we have referred to the newly discovered dwarf galaxy as Andromeda XXVIII, but this may not be the most accurate identifier to use. The dwarf is actually located in the constellation Pegasus, and could also be identified as Pegasus II, as is the convention with Milky Way and Local Group satellites. However, its properties make it a likely satellite of M31, and hence we follow the convention of naming satellites of M31 with the prefix Andromeda regardless of their actual position. Since we have neither its radial velocity nor its proper motion, we certainly cannot say whether the dwarf galaxy is bound to M31, but its distance to M31 is within the range of other galaxies in the M31 system, and it is much further from the Milky Way than we would expect for dwarfs bound to the Milky Way. If, upon further study, the galaxy is determined to be unbound from M31, then it should properly be referred to as Pegasus II. Further discussion of the complexities of dwarf galaxy names can be found in the Appendix of Martin et al. (2009).

The most intriguing feature of And XXVIII is its large distance from Andromeda, which suggests that it might not have been strongly affected by interactions with other galaxies. This could make it a prime test case for studies of dwarf galaxy formation. The morphology and star formation history of And XXVIII are of particular interest, as dwarf galaxies in the Local group that lay beyond 300–400 kpc from their

host tend to be dwarf irregular galaxies, while those in close proximity with their host tend to be dwarf spheroidals. This morphology–density relationship (Grebel et al. 2003) is not without exceptions; for instance, the dwarf spheroidals Tucana, Cetus, and the possible dwarf spheroidal And XVIII are all more than 400 kpc from the nearest non-dwarf galaxy. These distant dwarf spheroidals are a unique test for theories which suggest that dwarf spheroidals form from dwarf irregulars via tidal interactions or ram pressure stripping (Mayer et al. 2006; Weisz et al. 2011), since these galaxies could be in the beginning stages of such a process and could exhibit evidence of such an ongoing transformation. If And XXVIII were confirmed to be a dwarf spheroidal without any recent star formation, it would add another test case for these theories.

Alternatively, if star formation is detected in And XXVIII, it would be one of the lowest mass star-forming galaxies known and roughly analogous to LGS 3 (Thuán & Martin 1979) or Leo T (Irwin et al. 2007). The ability of such low-mass galaxies to retain gas and form stars is poorly understood, and identifying another member of this class of galaxies would benefit efforts to further elucidate their nature.

Unfortunately, with shallow SDSS imaging we cannot conclusively determine whether or not And XXVIII has ongoing or recent star formation. From the CMD of Leo T, the blue-loop stars that indicate recent star formation are roughly 1.5–2 mag fainter than the TRGB. Since the SDSS data of And XXVIII only extend approximately 1 mag below the TRGB, blue-loop stars are not detectable. We have also looked for H I in the galaxy using the Leiden/Argentine/Bonn Survey (Kalberla et al. 2005). This survey clearly detects the H I gas present in LGS 3 and Leo T ( $M_{\text{H I}} = 1.6 \times 10^5$ ,  $\sim 4.3 \times 10^5 M_\odot$ , respectively; Greivich & Putman 2009), but shows no emission from And XXVIII. This could, however, be the result of the velocity of the dwarf falling outside the bandwidth used for the survey ( $-400 < v_{\text{LSR}} < 400$  km s<sup>-1</sup>), so a conclusive determination of the H I gas content will require a measurement of the radial velocity of the galaxy.

Though the exact significance of And XXVIII will not be known until follow-up observations are conducted, it is clear that dwarf galaxies in the outer regions of the Local Group are

in a unique environment that enables their detailed study before their properties are significantly altered by interactions with their host galaxy upon infall. Increasing the sample of nearby but isolated dwarfs thus provides the data necessary to advance theories of dwarf galaxy formation and evolution.

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*Facility:* Sloan

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