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STRANGERS IN THE NIGHT: DISCOVERY OF A DWARF SPHEROIDAL GALAXY ON ITS FIRST LOCAL GROUP INFALL

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ABSTRACT

We present spectroscopic observations of the And XII dwarf spheroidal galaxy using DEIMOS/Keck II, showing it to be moving rapidly through the Local Group (-556 km s^{-1} heliocentric velocity, -281 km s^{-1} relative to Andromeda), falling into the Local Group from ∼115 kpc beyond Andromeda's nucleus. And XII therefore represents a dwarf galaxy plausibly falling into the Local Group for the first time and never having experienced a dense galactic environment. From Green Bank Telescope observations, a limit on the H I gas mass of $<3 \times 10^3\ M_\odot$ suggests that And XII's gas could have been removed prior to experiencing the tides of the Local Group galaxies. Orbit models suggest that the dwarf is close to the escape velocity of M31 for published mass models. And XII is our best direct evidence for the late infall of satellite galaxies, a prediction of cosmological simulations.

Subject headings: galaxies: evolution — galaxies: individual (Andromeda) — galaxies: spiral — Local Group

Online material: color figures

1. INTRODUCTION

Dwarf galaxies and stellar streams represent the visible remnants of the merging process by which the halos of galaxies are built up. They can be used to unravel the hierarchical formation of their host galaxies (White & Rees 1978). Dwarf galaxies are also the systems with the highest mass-to-light ratio found in the universe (e.g., Mateo et al. 1998), which make them one of the best laboratories for investigating the nature of dark matter (e.g., Peñarrubia et al. 2007).

In the cold dark matter paradigm a few Myr after the big bang, the distance between protodwarf galaxies and their hosts was much smaller. Early structure formation left dwarf galaxies over a large range of distances from the host galaxy with small radial velocity components (they were located approximately at their orbital apocenter). The largest dark matter overdensity in the local volume attracted these systems so that they eventually merged, moving on high eccentric orbits. In this picture, those substructures initially lying close to the parent galaxy were the first ones to be accreted, whereas those with large initial separations are either accreting now or have yet to accrete. An important prediction implicit in this scenario is that all accreting substructures are bound to the host galaxy; only strong interactions, like three-body encounters, might provide enough energy for them to escape the host systems. Also interesting is the fact that the late accretion events are expected to move on highly eccentric orbits, with large radial velocity components with respect to the host. Moreover, these systems correspond to the objects that formed farthest from the host galaxy, thus sampling a satellite galaxy population that has mostly lived in a very different environment from the Local Group. It is only now, after they have been accreted, when strong gravitational fields start to alter their original properties (mass, dark matter and distributions, gas fraction, etc.). High-speed dwarf galaxies, moving with velocities close to the escape velocity, therefore represent an interesting theoretical and observational target that might provide important insights into the effects of dynamical evolution on the properties of dwarf galaxies.

It is believed that the satellites of the Milky Way and M31 have been accreted at relatively early times, and their properties have been molded by their interactions with their parent galaxies. There will undoubtedly be mergers in the future of satellite systems within the Local Group (e.g., the Magellanic Clouds; Kallivayalil et al. 2006; Pedreros et al. 2006). There is also the case of the rather extreme orbit of the Leo I dwarf spheroidal (Mateo et al. 1998), which is now moving rapidly outward from the Local Group on the limit of being bound. Recent observations (Sohn et al. 2007) support a picture in which Leo I has been tidally disrupted on several perigalactic passages of a massive galaxy. Here we report on kinematic observations of And XII, a dwarf spheroidal that is a candidate for first infall into the Local Group.

2. OBSERVATIONS

The dwarf spheroidal galaxy And XII lies at 105 kpc (projected) from the nucleus of M31, the faintest dwarf galaxy in the M31 outer halo MegaCam/CFHT survey data (Martin et al. 2006; Ibata et al. 2007), with an overdensity of red giant branch (RGB) stars with similar metallicity (Fig. 1). And XII was followed up with imaging from a SUPRIMECam/Subaru survey of M31 halo substructures (N. Martin et al. 2007, in preparation) to improve the distance estimate to And XII and better understand its stellar populations. Spectra for candidate And XII stars were obtained with the DEIMOS spectrograph on the Keck II telescope (Figs. 1 and 2). Multi-object Keck observations with DEIMOS (Faber et al. 2003) were made on 2006 September 21–24, in photometric conditions and excellent seeing of 0.6″. We used the 600 line mm^{-1} grating, achieving resolutions ∼3.5 Å and probing the observed wavelength range from 0.56 to 0.98 μm. Exposure time was 140 minutes, split into 20 minute integrations. Data reduction followed standard techniques using the DEIMOS-

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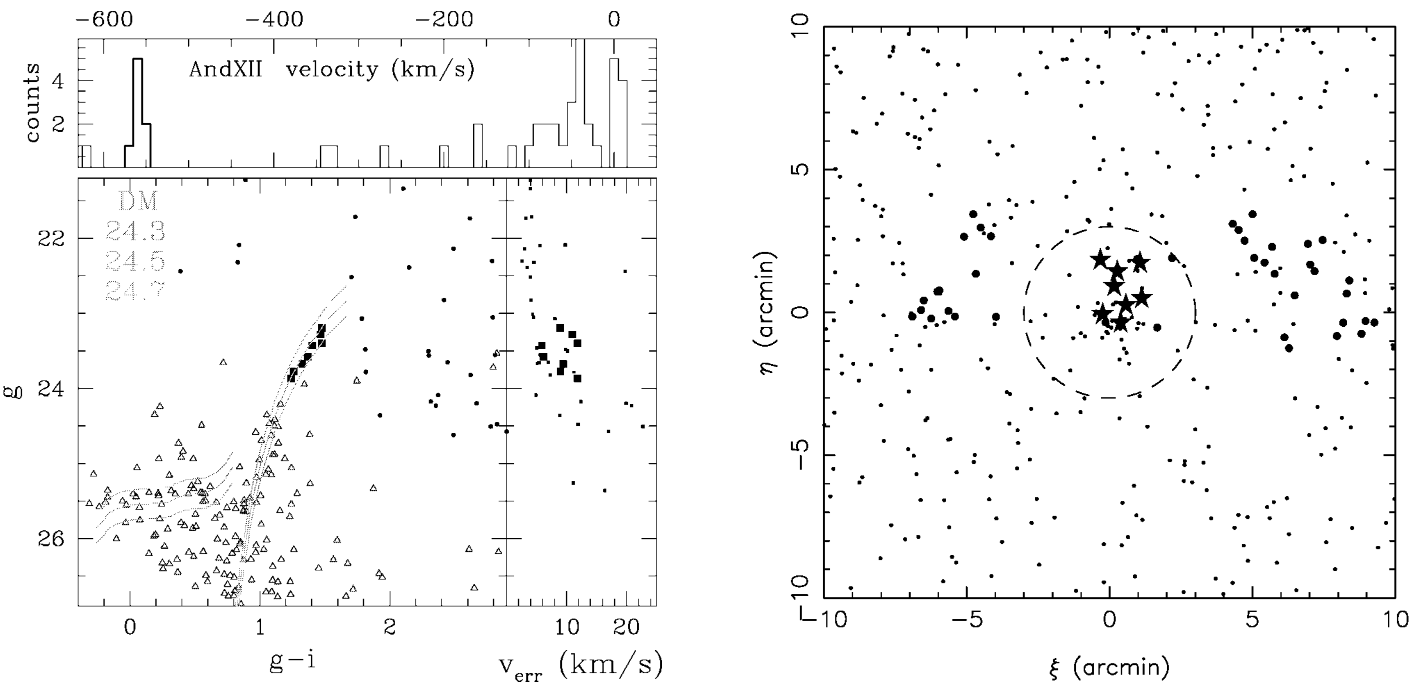

FIG. 1.—*Left*: On the top is shown the radial velocity histogram binned by 10 km s^{-1}. The eight stars in And XII are bold. Stars at >150 km s^{-1} are likely Galactic, while the remaining few stars are likely members of the outer halo of M31. On the left, the color-magnitude diagram of the field of And XII with the eight stars in And XII as large squares, the 49 stars with Keck radial velocities shown as squares, and all other stars within 3′ radius of And XII shown as open triangles. Stars selected for Keck spectroscopic follow-up were taken from the CFHT-MegaCam image. All other stars are shown from the Subaru SUPRIMECAM image. Best-fitting isochrones from the library of Girardi et al. (2004) are overlaid, with [Fe/H] $= -1.5$, log(age) = 10.25, and distance moduli of 24.3, 24.5, and 24.7. On the right is shown the velocity errors for the 49 stars with radial velocity measurements. *Right*: Representation of the dwarf galaxy And XII showing all stars with photometric metallicity $-2.3 <$ [Fe/H] < -1.3 (Table 1 stars highlighted, as well as the other 41 stars with DEIMOS velocities *not* lying in And XII) in the CFHT MegaCam M31 survey (Martin et al. 2006; Ibata et al. 2007). [*See the electronic edition of the Journal for a color version of this figure.*]

DEEP2 pipeline (Faber et al. 2003), debiasing, flat-fielding, extracting, wavelength-calibrating, and sky-subtracting the spectra.

The radial velocities of the stars were then measured with respect to a Gaussian model of the Calcium-II triplet (CaT) absorption lines (Wilkinson et al. 2004). By fitting the three strong CaT lines separately (Fig. 2), an estimate of the radial velocity accuracy was obtained (Table 1), with typical uncertainties of 5–12 km s^{-1}, before accounting for systematic errors from sky lines (which can add another 5–10 km s^{-1}). Close to the center of And XII there is a clear kinematic grouping of eight stars with cross-correlation peaks greater than 0.1 at a velocity of ~ -556 km s^{-1} heliocentric, which also lie on the And XII RGB (Fig. 1). This corresponds to -281 km s^{-1} relative to M31 after removing Milky Way motions. Although we targeted 49 stars in the vicinity of the And XII overdensity, no other stars are associated with this dwarf by their kinematics; all other stars lie more than 5 σ away from the kinematic grouping of stars associated with the And XII color-magnitude diagram. The And XII stars have a velocity dispersion of 5 km s^{-1} before accounting for instrumental errors; however, the velocity errors are sufficiently large that a meaningful limit on the mass of And XII is difficult to constrain. An average metallicity of [Fe/H] $= -1.9 \pm 0.2$ is estimated for And XII from the equivalent widths of the CaT lines of the combined spectrum in Figure 2, adopting the technique described in Ibata et al. (2005). However, the five highest S/N spectra have a more metal-rich median, [Fe/H] $= -1.7$, closer to the photometric [Fe/H] $= -1.5$ (Martin et al. 2006).

We also searched for neutral hydrogen at rest frequency 1420.406 MHz, shifted to the systemic velocity of And XII. Using the Green Bank Telescope (2006 November 29) and the 12.5 MHz bandwidth of the spectrometer, we integrated on And XII using interspersed on/off observations totaling 1 hr each. The 9.8′ beam size implies that the full stellar extent of And XII is well within the beam. There is no detection down to 2.53 mJy rms, suggesting a limit on the H I gas mass of $<3 \times 10^3\ M_\odot$ for an assumed line width of 4 km s^{-1} (comparable to the raw dispersion of the RGB stars).

TABLE 1

POSITIONS AND PARAMETERS OF THE EIGHT STARS CONFIRMED AS ASSOCIATED WITH AND XII

R.A.	Decl.	Velocity	Vel-Error	*g*-Mag	*i*-Mag
0 47 31.04	34 24 12.1	−557.2	6.9	23.028	21.642
0 47 24.69	34 22 23.9	−565.8	10.1	23.129	21.658
0 47 27.76	34 22 6.2	−556.9	4.9	23.214	21.744
0 47 28.63	34 22 43.1	−561.0	5.1	23.382	21.974
0 47 31.34	34 22 57.6	−555.0	7.4	23.504	22.156
0 47 26.65	34 23 22.8	−548.1	10.5	23.880	22.542
0 47 27.18	34 23 53.5	−550.4	7.0	23.883	22.532
0 47 30.60	34 24 20.3	−559.5	11.2	23.903	22.657

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

3. RESULTS

Our new data measure the radial motion and constrain the distance to And XII. Since our spectroscopy tells us which among the candidates are definite And XII RGB stars, we can assess the distance directly. We first fit isochrones from the library of Girardi et al. (2004) to the RGB, assuming the oldest age in the library [log(age) = 10.25]; younger ages make the fits worse and the implied radial distance larger. Template isochrones were first extinction-corrected using the Schlegel et al. (1998) extinction maps, $E(B-V) = 0.11$. We then attempted to fit isochrones of [Fe/H] $= -2.3, -1.7, -1.5$, and -1.3, over a range in distance modulus (DM) from 24.1 to 24.9 (M31 has

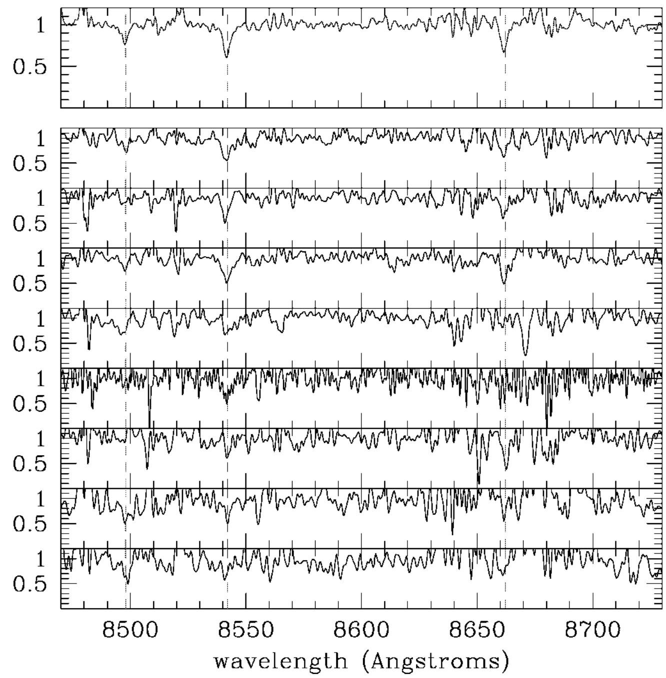

FIG. 2.—Eight individual spectra, and the combined spectrum of stars from Table 1 (smoothed to the instrumental resolution) spanning the $i =$ 21.6–22.6 range. The CaT lines are shown in the rest frame, with spectra shifted to zero velocity. [*See the electronic edition of the Journal for a color version of this figure.*]

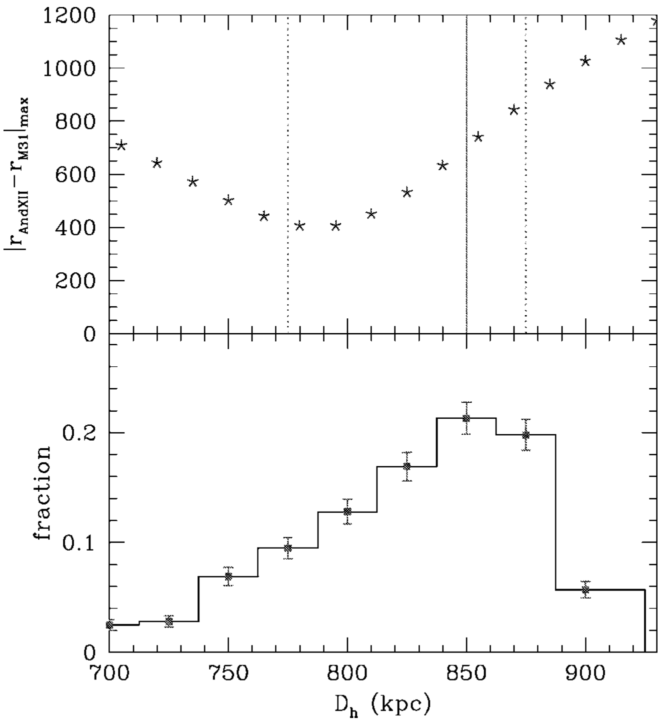

FIG. 3.—*Top*: Distance And XII would have reached from M31 in the last 10 Gyr, 725 kpc for the most probable radial distance from the TRGB resampling distribution. *Bottom*: Heliocentric distance probability curve for And XII, derived using our TRGB analysis and calibrated to an isochrone fit to the RGB and HB. [*See the electronic edition of the Journal for a color version of this figure.*]

a DM $= 24.47$ and a $I_{0,\,\mathrm{Vega,\,TRGB}} = 20.54$; McConnachie et al. 2005). The best-fitting isochrones are overlaid in Figure 1, with [Fe/H] $= -1.5$, DM $= 24.5$ ($D_{\mathrm{hel}} = 810$ kpc) being the best overall fit to the RGB and likely horizontal branch stars. Fits to the RGB shape and horizontal branch region were worse with other metallicities. Further analysis of the stellar populations in And XII will be presented in N. Martin et al. (2007, in preparation). To assess a likely error range on the distance, we then employed the "tip of the red giant branch" (TRGB) technique (e.g., McConnachie et al. 2004). An absolute upper limit to the radial distance can be obtained by assuming the brightest RGB star ($I_{0,\,\mathrm{Vega}} = 20.95$) is at the TRGB. This implies $D_{\max} = 950$ kpc (Fig. 3). To constrain the minimum distance, we must assess what the maximum possible offset could be from this brightest RGB star. In the absence of knowledge of the luminosity function of And XII, we analyze the well-populated RGB of the dwarf spheroidal, And II (McConnachie et al. 2005). Our Girardi et al. (2004) isochrone fit to the RGB suggests that our eight confirmed members of And XII lie within the top magnitude of the RGB. With 1000 random samples of eight of the brightest stars from the top magnitude of the And II RGB, we constrain a probability distribution for the true TRGB for And XII (corresponding to offsets up to 0.5 mag) and thereby the likely range of distances (Fig. 3). The median distance for And XII is 830 ± 50 kpc (interquartile range), in excellent agreement with the simple isochrone fit performed earlier, and updates the derived parameters of And XII: M_v becomes -6.9, and the half-light radius, r_{hb}, becomes 137 pc (previously estimated as 125 pc).

Figure 3 summarizes our model of orbits for And XII. Integrating the orbit back in time necessitates that And XII likely came from beyond the Local Group's virial radius. We adopt a recently published mass model for M31 (Geehan et al. 2006), dominated by a NFW (Navarro et al. 1997) dark matter halo with total virial mass of $\sim 1 \times 10^{12}\ M_{\odot}$. An object traveling at -281 km s^{-1} with respect to M31 at time zero (today) is considered over all possible heliocentric distances in the gravitational potential of M31. And XII likely reached distances close to 725 kpc beyond M31 in the previous 10 Gyr (a substantial part of the journey to the neighboring galaxy concentration around M81) and is an excellent candidate for a dwarf falling into the Local Group for the first time.

The high radial velocity of And XII, together with the large separation from its apparent host, M31, suggest that And XII's orbit might be highly eccentric, close to the limit of being bound to M31 and the Local Group. Figure 4 shows And XII relative to the circular and escape velocities of M31 in the Geehan et al. (2006) model. And XII is the most extreme satellite of M31, even more so than recently discovered satellites And XIV (Majewski et al. 2007), And XI, and And XIII (Martin et al. 2006, Chapman et al. 2007). In a CDM framework, subhalos cannot be accreted exceeding the escape velocity unless they suffered strong three-body interactions. In this framework, And XII places a lower limit on the mass of M31 slightly larger than estimates from the present models (Fig. 4; Geehan et al. 2006). There is also an unknown proper (transverse) motion to add to the radial velocity—it is unlikely for And XII to be approaching head-on, and therefore it might be falling into the Local Group faster than the limiting $v_{\mathrm{hel}} = -556$ km s^{-1}.

4. DISCUSSION

Theoretical considerations have suggested that even at the present day, galaxies should still be falling into the Local Group from surrounding overdense structures. Benson (2005) measured the orbital parameters of infalling substructures from N-body simulations. There was little evidence for any mass dependence in the distribution of orbital parameters, and so the

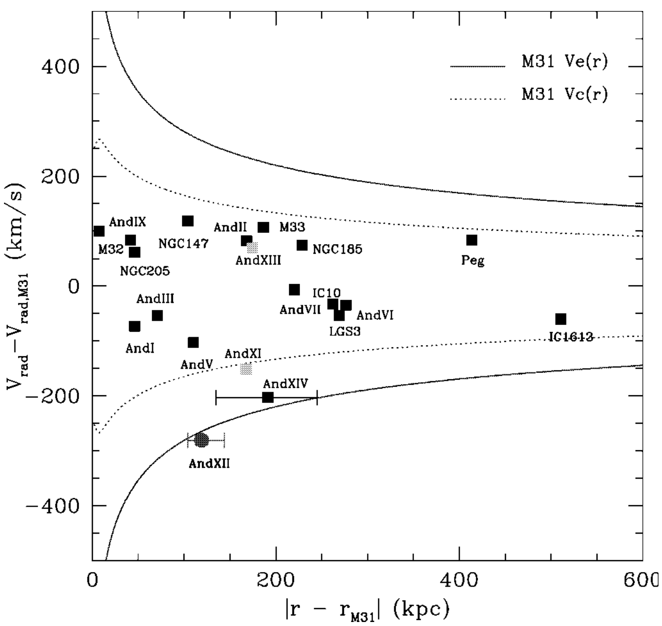

FIG. 4.—Escape velocity is shown for M31 assuming the Geehan et al. (2006) mass model (*solid line*), derived from the circular velocity (*dashed line*), as a function of three dimensional distance of M31 from its satellites (data from Cote et al. 2000, and McConnachie et al. 2005). And XII is shown with a circle. Recently discovered satellites And XIV (Majewski et al. 2007), And XI, and And XIII (Martin et al. 2006; Chapman et al. 2007) are highlighted. [*See the electronic edition of the Journal for a color version of this figure.*]

results are expected to be applicable to And XII. The orbital parameters in the Benson (2005) simulations were determined at the point at which the substructure first entered the virial radius of the larger halo.

The large velocity and likely distance behind M31 suggest that And XII is falling into the Local Group for the first time. The most likely place where systems like And XII form is in filaments. A. Ludlow et al. (2007, in preparation) have looked explicitly at high-velocity structures falling into halos of similar total mass to the Local Group at late times. Substructures that have yet to fall into the surrogate Local Group clearly lie within a filamentary morphology.

At late times (today), one observes subhalos in *N*-body cosmological simulations with high velocities because a large fraction of them move on parabolic orbits. The ones that move outward are those that accreted many Gyr ago and are now close to escaping, perhaps the situation with Leo I (Mateo et al. 1998) and And XIV (Majewski et al. 2007). The ones that move inward, like And XII, are those that were accreted later.

If And XII has not yet experienced the strong gravitational environment of the Local Group, its H I gas content could be an interesting evolutionary constraint. Mayer et al. (2005, 2007) show that assuming a low density of the hot Galactic corona consistent with observational constraints, dwarfs with $V_{peak} <$ 30 km s^{-1} will be completely stripped of their gas content on orbits with pericenters of 50 kpc or less. In these objects most of the gas is removed or becomes ionized at the first pericenter passage, explaining the early truncation of the star formation observed in Draco and Ursa Minor. Galaxies on orbits with larger pericenters and/or falling into the Local Group at late times (like And XII) should retain significant amounts of the centrally concentrated gas. These dwarfs would continue to form stars over a longer period. While the dark matter mass in And XII is uncertain, it is plausibly $>10^6\ M_\odot$, with an initial gas mass of $>10^4\ M_\odot$. If And XII has not yet passed through the potential of the Local Group and no longer has a sizeable gas supply ($<3 \times 10^3\ M_\odot$ from our GBT measurement), it must have been stripped of its neutral H I through other means, perhaps some of it through its Population III stars.

While the precise direction of origin is uncertain because of the unknown tangential velocity, And XII could have come roughly from the direction of the Sculptor group and beyond toward the M81 group, although it could not have traversed the distance from the M81 group (~3.5 Mpc; Karachentsev et al. 2002) in the age of the universe. The discovery of And XII presents the best piece of evidence to date for the late accretion of satellites and sets a new benchmark for testing the mass of Local Group galaxies and simulations of galaxy formation.

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