DISCOVERY OF AN UNUSUAL DWARF GALAXY IN THE OUTSKIRTS OF THE MILKY WAY

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ABSTRACT

We announce the discovery of a new dwarf galaxy, Leo T, in the Local Group. It was found as a stellar overdensity in the Sloan Digital Sky Survey Data Release 5 (SDSS DR5). The color-magnitude diagram of Leo T shows two well-defined features, which we interpret as a red giant branch and a sequence of young, massive stars. As judged from fits to the color-magnitude diagram, it lies at a distance of ∼420 kpc and has an intermediate-age stellar population with a metallicity of [Fe/H] = −1.6, together with a young population of blue stars of age ∼200 Myr. There is a compact cloud of neutral hydrogen with mass ∼$10^5 M_\odot$ and radial velocity +35 km s^{-1} coincident with the object visible in the HIPASS channel maps. Leo T is the smallest, lowest luminosity galaxy found to date with recent star formation. It appears to be a transition object similar to, but much lower luminosity than, the Phoenix dwarf.

Subject headings: galaxies: dwarf — galaxies: individual (Leo) — Local Group

1. INTRODUCTION

The last 2 years have seen the discovery of 10 faint, new Milky Way satellites in data from the Sloan Digital Sky Survey (SDSS). This is made up of eight new Milky Way dwarf galaxies, together with two unusually extended globular clusters (Willman et al. 2005; Zucker et al. 2006a, 2006b; Belokurov et al. 2006a, 2007). The purpose of this Letter is to announce the discovery of an additional dwarf galaxy in the Local Group. At a heliocentric distance of ∼420 kpc, this is at the very outskirts of the Milky Way's sphere of influence.

The dwarf is faint with roughly circular isopleths from the majority intermediate-age stellar population. These properties are shared by other Local Group dwarf spheroidal (dSph) galaxies. However, Leo T also has a population of bright, blue stars, which is evidence for an epoch of recent star formation. It must therefore have contained some gas in the recent past, and there is evidence of a compact, neutral gas cloud still associated with the object today. These properties are characteristic of the dwarf irregular (dIrr) galaxies. As the dwarf possesses transitional properties—intermediate between those of dSph and dIrr galaxies—we propose to call it Leo T. Other transitional dwarf galaxies are known, in particular Phoenix, Pisces, and Leo A (see, e.g., Grebel 2001), which are at comparable distances from the Galaxy and M31.

2. DATA AND DISCOVERY

SDSS imaging data are produced in five photometric bands, namely, *u*, *g*, *r*, *i*, and *z* (Fukugita et al. 1996; Gunn et al. 1998, 2007; Hogg et al. 2001; Adelman-McCarthy et al. 2006). The data are automatically processed through 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) and dereddened with the help of Schlegel et al. (1998). DR5 primarily covers ∼8000 deg^2 around the North Galactic Pole.

As part of our systematic survey of stellar overdensities in DR5 (Belokurov et al. 2006b, 2007), we identified a new candidate in the constellation of Leo. A roughly spherical overdensity of objects classified by the SDSS pipeline as stars is readily visible in the left panel of Figure 1. Plotting these stars in a color-magnitude diagram (CMD) and using it to construct a Hess diagram (right panels of Fig. 1) reveals a clear red giant branch (RGB). Although sparsely populated, the CMD looks like those of the dIrr or transition galaxies with detected young, blue populations, such as Phoenix (Martínez-Delgado et al. 1999) and Leo A (Tolstoy et al. 1998). The bright, blue sequence in the CMD may be a nearly zero-age main sequence or blue loop, or even blue straggler stars. Some of the stars may even be blue horizontal branch stars scattered into this region of the CMD by photometric errors. Precise interpretation needs deeper photometry, but the general conclusion is clear—the Leo T dwarf contains a population of young, recently formed (<1 Gyr) stars.

The distance, metallicity, and age of the object were constrained by applying a CMD fitting technique to the SDSS photometry. Using the MATCH software (Dolphin 2002; de Jong et al. 2007) together with isochrones from Girardi et al. (2004), model stellar populations with fixed age range, metallicity, and distance were fit to the *g* − *r* versus *r* data for all stars within 6.0′ of the center. The background was estimated using stars located suitably far from the object. Figure 2 shows the goodness-of-fit contours for two different age bins, namely, 4–5 and 8–10 Gyr. The inset shows the improvement in the maximum likelihood goodness-of-fit parameter *Q* (Dolphin 2002) for the ages probed with respect to fitting a control field CMD. While the age of the stellar population is not well constrained, the best-fit metallicity and distance values do not change significantly. These fits imply a rather metal-poor stellar population with [Fe/H] ∼ −1.6 at a distance modulus of ∼23.3 mag, corresponding to a heliocentric distance of ∼450 kpc. The fits are heavily weighted toward the most numerous population in the CMD, in this case the RGB population.

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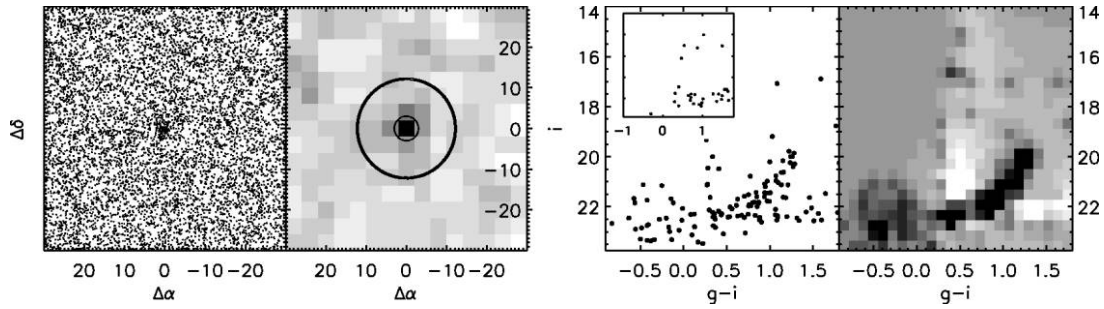[7] Gemini Observatory, Hilo, HI.

FIG. 1.—Leo T Dwarf. *Left*: Spatial distribution of all objects classified as stars in the vicinity of Leo T. $\Delta\alpha$ and $\Delta\delta$ are given in arcminutes. *Middle left*: Binned spatial density of all stellar objects. The inner circle marks a radius of $3'$, and the outer circle a radius of $12'$. Bins are $4' \times 4'$, smoothed with a Gaussian with a FWHM of $6'$ *Middle right*: CMD of all stellar objects within the inner $3'$ radius circle; note the RGB. The inset shows a control CMD with all stellar objects in an annulus between $12.0'$ and $12.4'$ of the center. *Right*: A color-magnitude density plot (Hess diagram), showing the inner CMD minus a larger area control CMD, appropriately normalized. The red giant branch is clearly seen, along with another blue feature discussed in the main text.

3. PHYSICAL PROPERTIES AND STELLAR POPULATION

Follow-up observations of Leo T were made on 2006 November 30 (UT) using the 2.5 Isaac Newton Telescope (INT) with the Wide Field Camera (WFC). This contains four 2k × 4k pixel EEV CCDs with a field of view of roughly $30' \times 30'$ and a scale of $0.33''$ pixel^{-1} at the field center. Leo T was observed with single exposures of 1200 and 900 s in SDSS-like g, r bands, and calibrated on the SDSS AB system. Data were processed in Cambridge using a general purpose pipeline for processing wide-field optical CCD data (Irwin & Lewis 2001). Images were debiased and trimmed, cross-talk–corrected, and then flat-fielded and gain-corrected to a common internal system using clipped median stacks of nightly twilight flats. For each image frame an object catalog was generated using the object detection and parameterization procedure discussed by Irwin et al. (2004). Objects in the catalogs were morphologically classified as stellar or nonstellar (or noise-like). The detected objects in each passband were then merged by positional coincidence (within $1''$) to form a combined catalog.

Figure 3 shows an INT image derived from the g- and r-band data. The Leo T dwarf is clearly visible, together with its popu-lation of blue stars. The left panels of Figure 4 show the CMD within a $1.8'$ radius of the center. Even though the giant branch is sparsely populated, the tip must be as bright as $i \sim 19.8$ (see Fig. 1), which corresponds to $I \sim 19.3$, using the transformations given in Smith et al. (2002) and allowing an extra 0.06 mag for extinction in the i band. Using the calibration $I_{\mathrm{TRGB}} = -4.03$ (Bellazzini et al. 2001), we find that the distance modulus is therefore at most 23.3.

The rightmost panel of Figure 4 shows the luminosity functions of stars detected in the g-band image (see Fig. 3), which is complete to $g \sim 25$. The black line shows the number of stars within a circle of radius $4.2'$. This is compared with the gray line, which shows the appropriately normalized luminosity function for the background region. There is an obvious excess of counts peaking at $g \sim 23.8$, which is where we would expect to see the horizontal branch. This unambiguous detection, which is readily apparent in the CMDs shown in the left panels, allows us to improve on the distance estimate. Assuming $M_{\mathrm{HB}} = 0.6$ in the g band at $g - r \approx 0$ after allowing for extinction implies a distance modulus of 23.1 ± 0.1, consistent with the sparsely
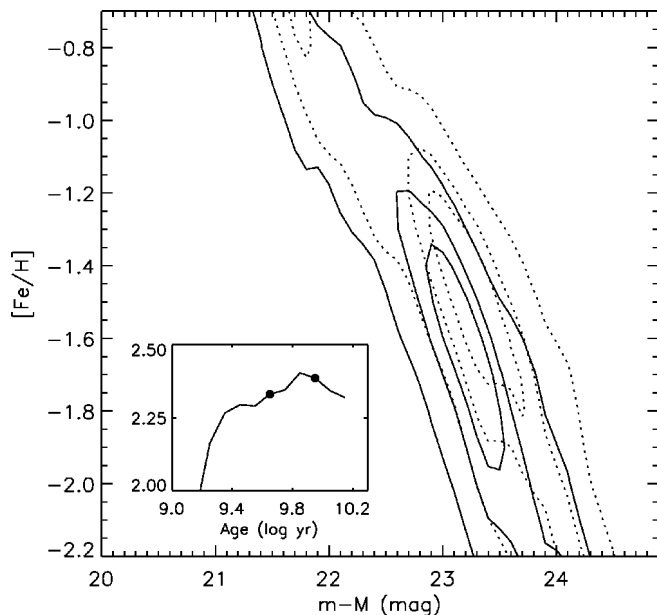

FIG. 2.—Goodness-of-fit contours of CMD fits using the method of de Jong et al. (2007) for two different populations with ages 4–5 Gyr (*dotted line*) and 8–10 Gyr (*solid line*). The levels correspond to 0.5, 1, and 2 σ uncertainties. The inset shows the improvement in the maximum-likelihood goodness-of-fit parameter Q (Dolphin 2002) with circles representing the two populations.

FIG. 3.—Color image covering a $6.5' \times 6.5'$ region centered on the Leo T dwarf made from INT WFC data in the g and r bands. North is up, and east is to the left.
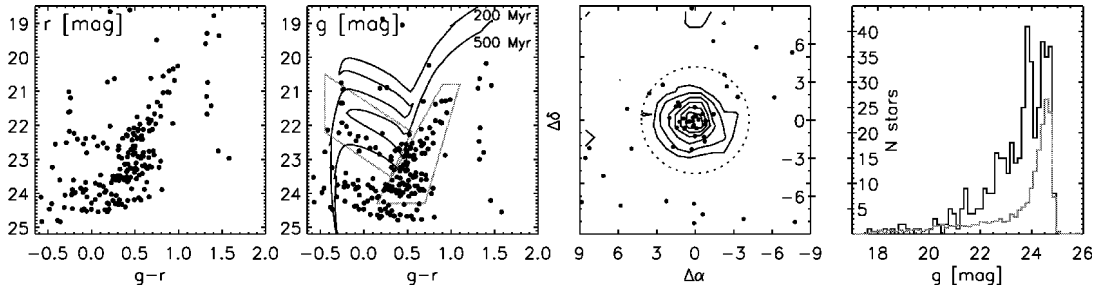
Fig. 4.—*Left and middle left*: CMDs in $g - r$ vs. r and g based on INT imaging data within a radius of 1.8′ of the center of Leo T. The light gray boxes enclose the RGB and young blue candidate stars. Overplotted are isochrones from Girardi et al. (2004) for [Fe/H] = −1.7 and age 200 and 500 Myr. *Middle right*: The density contours of the RGB candidates in a box 18′ × 18′ centered on Leo T, together with the locations of the possible young blue stars. *Right*: The g-band luminosity function within the dotted circle (*black*) compared to the background (*gray*). There is a clear detection of the horizontal branch at $g \sim 23.8$.

populated RGB near the tip. The middle left panel of Figure 4 shows overlaid isochrones from Girardi et al. (2004) corresponding to stellar populations of age 200 and 500 Myr at a distance modulus of 23.1. Blue stars brighter than $g = 23$ and blueward of the giant branch are therefore most likely to be helium-burning blue loop stars associated with a young component. Two zones from the CMD, indicated by the gray boxes, were used for the spatial analysis. The RGB candidates were used to produce the density contours in the middle right panel of the figure. The object is seen to be almost circular in the inner parts. The young blue stars are shown as filled circles in this figure and are concentrated near the center, thus confirming that they are physically associated with the Leo T dwarf.

To estimate the properties in Table 1, we use the INT data to derive the centroid from the density-weighted first moment of the distribution and use the second moments to investigate the ellipicity. Although circular in general appearance the ellipticity at different contour levels averages ∼0.1 but has a position angle that varies by 90°. The radial profile shown in Figure 5 is derived from all stars with $g - r < 1$ and satisfying $20 < g < 25$. We compute the average density within circular annuli after first subtracting a constant asymptotic background level (0.8 arcmin^{-2}), reached at large radii, and then fit the radial profile with a standard Plummer law. At a distance of ∼420 kpc, the best-fitting half-light radius of 1.4′ corresponds to ∼170 pc. This is the typical scale length of some of the recently discovered Galactic dSph galaxies (Belokurov et al. 2007) but smaller than the classical Local Group dIrr galaxies (van den Bergh 2000).

The flux (AB magnitudes) in stars within a 5′ radius relative to a control background region is $g = 17.1$ and $r = 16.7$ computed by integrating to the horizontal-branch level. To estimate

the contribution from young stars between the horizontal branch and main-sequence turnoff, we used the deep *Hubble Space Telescope* luminosity function of Phoenix provided by Holtzman et al. (2006) to obtain a correction of 0.5 mag. By allowing 0.3 mag for stars fainter than turnoff, and 0.1 mag for extinction, we obtain a total flux estimate of $g = 16.2$. Using the transformations in Smith et al. (2002) and assuming the measured average color of $g - r = 0.4$ holds for the entire stellar population, this equates to $V = 16.0$ (Vega). At a distance modulus $(m - M)_0 = 23.1$, this corresponds to an absolute magnitude of $M_V = -7.1$. Assuming a Plummer profile, this yields an observed V-band central surface brightness of ∼27.0 mag arcsec^{-2}. For the new dwarfs this is a relatively high surface brightness, which is consistent with the easy visibility on the image in Figure 3.

Finally, Figure 6 shows an H I flux density map centered on the coordinates of the Leo T dwarf using data from the Northern H I Parkes All Sky Survey (HIPASS; Wong et al. 2006). Located at the same spot is a significant H I overdensity. At a distance of ∼420 kpc, the H I mass of this cloud would be $2 \times 10^5 \, M_\odot$. Its flux-weighted heliocentric velocity is 35 km s^{-1}, corresponding to a Galactic standard of rest velocity of −61 km s^{-1}, consistent with gentle Galactic infall. It is clearly isolated from the filamentary foreground of H I clouds, which have similar velocities. The stellar center of Leo T lies within the same 4′ × 4′ HIPASS pixel that
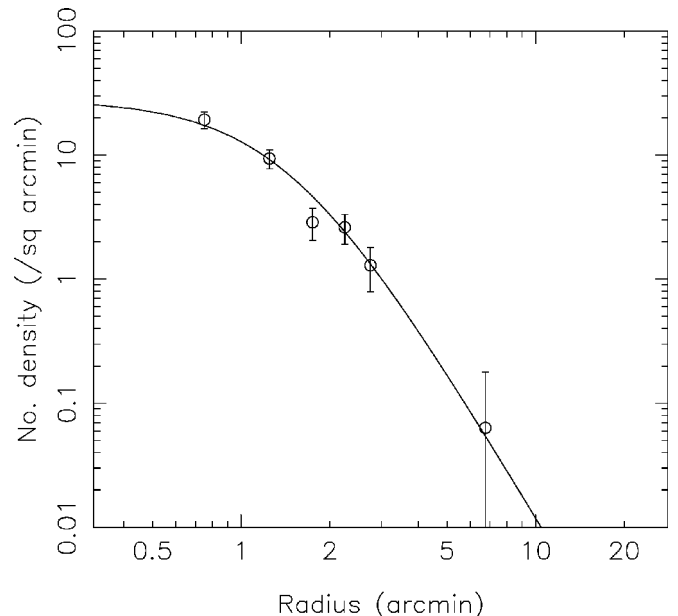
TABLE 1
PROPERTIES OF THE LEO T DWARF

Parameter[a]	Value
Coordinates (J2000.0)	$09^h34^m53.4^s$; $+17°03′05″$
Coordinates (Galactic)	$\ell = 214.9°$, $b = 43.7°$
Position angle	≈0°
Ellipticity	≈0
r_h (Plummer)	1.4′
A_V	0.1 mag
$\mu_{0,V}$ (Plummer)	26.9 mag
V_{tot}	16.0 mag
$(m - M)_0$	23.1 mag
$M_{tot,V}$	−7.1 mag
M_{HI}	$10^5 \, M_\odot$
$v_\odot$[b]	+35 km s^{-1}

[a] Surface brightnesses and integrated magnitudes are accurate to ∼±0.3 and are corrected for the mean Galactic foreground reddening, A_V, shown.

[b] From H I data, no stellar velocities measured to date.

Fig. 5.—Radial density profile of the Leo T dwarf based on INT data (all stellar objects with $g - r < 1.0$ and $g < 25.0$) together with a Plummer law fit.
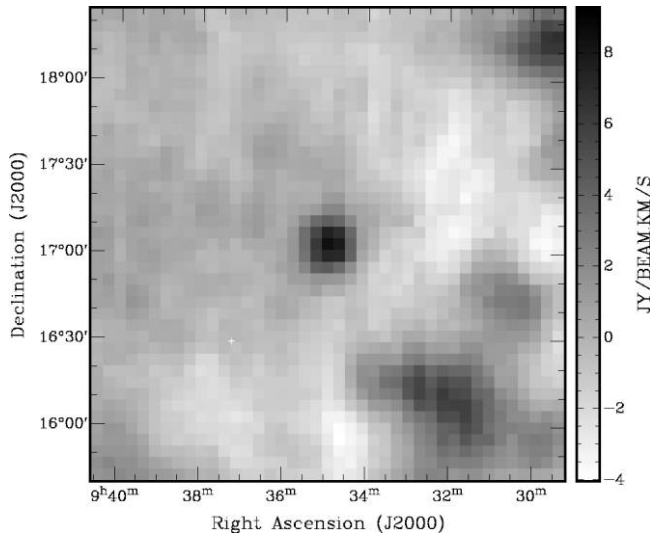
FIG. 6.—Integrated H I flux density map centered on the coordinates of the Leo T dwarf. Significant H I is detected in two adjacent velocity channels of data from HIPASS (Wong et al. 2006). The above map is the sum of these two adjacent velocity planes. The velocity channel separation of the HIPASS data is 13.2 km s^{-1}. The integrated flux density within the 15.5′ beam centered on this source is 4.9 Jy km s^{-1}. The detected point source, which has a flux-weighted heliocentric velocity of 35 km s^{-1}, does not appear to be connected to the undulating H I emission belonging to the Galactic interstellar medium.

contains the centroid of the HIPASS gas cloud. This suggests that there is a high probability that the cloud is physically associated with the dwarf. Although HIPASS does not have adequate velocity resolution to measure the dispersion directly, the nonappearance of the compact H I cloud in adjacent channels on either side of the two detection channels constrains the velocity dispersion to be less than ∼13 kms^{-1}, which is within the realm of low-luminosity dwarfs.

The stellar luminosity of Leo T is ∼4 × 10^4 $L_\odot$, which corresponds to a mass of ∼10^5 $M_\odot$, assuming a stellar mass-to-light ratio of ∼2–3. This gives a ratio of mass in H I to mass in luminous material $M_{H I}/M_L$ of about unity, consistent with that found in dIrr galaxies in the Local Group. The source is unresolved in HIPASS; however, the inferred average column density of H I within the Plummer radius is ∼2 × 10^{20} cm^{-2}. Although this average is slightly below the threshold required for star

formation (Elmegreen & Parravano 1994), the surface density of H I is likely to contain local peaks (van Zee et al. 1997).

4. CONCLUSIONS

We have discovered a new dwarf galaxy in the constellation of Leo, which we have named Leo T. Its CMD has a clear red giant branch, from which we derive a tentative age of 6–8 Gyr and a metallicity of [Fe/H] ∼ −1.6. Its distance, derived from the position of the horizontal branch, is ∼420 kpc. Given this distance, Leo T is unlikely to have been strongly affected by the tides of the Milky Way. This suggests that its very low luminosity is intrinsic and not the result of disruption or stripping. Clearly visible in the CMD is a sequence of bright blue stars indicative of recent star formation. Coincident with the position of the dwarf is an H I cloud of ∼2 × 10^5 $M_\odot$. The Leo T dwarf has some of the characteristics of transition galaxies like Phoenix or Pisces, but with an absolute magnitude of M_V ∼ −7.1, it is much fainter. It is the least luminous galaxy found to date with recent star formation.

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