URSA MAJOR: A MISSING LOW-MASS CDM HALO?

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ABSTRACT

The recently discovered Ursa Major dwarf spheroidal (dSph) galaxy candidate is about 5–8 times less luminous than the faintest previously known dSphs, And IX, Draco, and Ursa Minor. In this Letter, we present velocity measurements of seven color-magnitude–selected Ursa Major candidate stars. Two of them are apparent non-members based on metallicity and velocity, and the remaining five stars yield a systemic heliocentric velocity of \( \bar{v} = -52.45 \pm 4.27 \) km s\(^{-1}\) and a central line-of-sight velocity dispersion of \( \langle v^2 \rangle^{1/2} = 9.3^{+15.7}_{-13.1} \) km s\(^{-1}\), with 95% confidence that \( \langle v^2 \rangle^{1/2} > 6.5 \) km s\(^{-1}\). Assuming that UMa is in dynamical equilibrium, it is clearly dark matter–dominated and cannot be a purely stellar system like a globular cluster. It has an inferred central mass-to-light ratio of \( M/L \sim 500 \, M_{\odot}/L_{\odot} \), and, based on our studies of other dSphs, may possess a much larger total mass-to-light ratio. UMa is unexpectedly massive for its low luminosity—indeed, UMa appears to be the most dark matter–dominated galaxy yet discovered. The presence of so much dark matter in UMa immediately suggests that it may be a member of the missing population of low-mass galaxies predicted by the cold dark matter (CDM) paradigm. Given the weak correlation between dSph mass and luminosity, it is entirely likely that a population of dark dwarfs surrounds our Galaxy.

Subject headings: celestial mechanics, stellar dynamics — dark matter — galaxies: individual (Ursa Major dwarf) — galaxies: kinematics and dynamics — Local Group

1. INTRODUCTION

All of the Local Group dwarf spheroidal (dSph) galaxies have velocity dispersions much larger than expected for self-gravitating stellar systems, implying that their dynamics is dominated by dark matter, with the stars being little more than dynamical tracers within a dark halo (e.g., Mateo 1998). Some dSphs have central mass-to-light ratios of \( \sim 100 \, M_{\odot}/L_{\odot} \) and average mass-to-light ratios of several hundred (e.g., Kley na et al. 2001, 2004; Wilkinson et al. 2004).

Recently, Willman et al. (2005) discovered a new candidate dSph in Ursa Major in a search of data from the Sloan Digital Sky Survey (SDSS; Abazajian et al. 2005). Located about 100 kpc from the Galaxy, it has a half-light radius of \( r_{1/2} \sim 250 \) pc, covering \( 7.75 \) on the sky. Most remarkably, with \( M_v \sim -6.75 \), it is about 5 times less luminous than the faintest previously known dSph, Andromeda IX (Zucker et al. 2004; Chapman et al. 2005), and about 8 times less luminous than the faintest Galactic dSphs, Ursa Minor and Draco (Mateo 1998).

In this Letter, we describe precise radial velocity measurements of seven UMa candidate stars. We compute UMa’s inferred central density and mass, and discuss how UMa fits into the rest of the dSph population within the context of standard CDM theory.

2. DATA

We selected candidate stars from Data Release 3 of SDSS, picking targets within 6’ of UMa’s position as given by Willman et al. (2005). Figure 1 shows the color-magnitude diagram of the central 6’ region, slightly smaller than Willman’s half-light radius \( r_{1/2} = 7.75 \). The giant branch and horizontal branch are both visible, although together they contain only about 50 stars. Our seven targets (Fig. 1, filled circles) were drawn from the brightest part of the giant branch and span the magnitude range \( i = 17.45 \pm 18.38 \). We also observed the bright velocity standards HD 107328, HD 90861, and HD 132737.

We observed our stars using the upgraded HIRES (Vogt et al. 1994) echelle spectrograph on the Keck I telescope on the night of 2005 May 17. Each star was observed in one integration lasting 1800 s. The long spectral coverage of the spectrograph allowed us to obtain wavelengths from Ha (6564 Å) to the redmost line of the calcium triplet (8662 Å). The signal-to-noise ratio (S/N) varied among the spectra from \( S/N = 12–3 \) pixel\(^{-1}\), or \( S/N = 61–17 \) Å\(^{-1}\). Only the redmost Ca triplet line was near a sky line, but sky subtraction was generally clean even in this case.

We extracted the spectra using the MAKEE data reduction package for HIRES, creating flux and variance spectra for each echelle order. Because the latest version of MAKEE for the new three-chip upgrade to HIRES does not at present solve for the dispersion, we fit the dispersion solution manually for the relevant echelle orders using IRAF. All calibration arc exposures had to be taken during the afternoon or morning because of persistent ghosting with the new chips. To verify instrument stability, we measured the positions of sky lines in the science exposures, and found them to be constant within 0.2 km s\(^{-1}\).

For each of the four stellar absorption lines of interest (Ha and the three Ca lines), we cross-correlated a synthetic Gaussian template with the appropriate echelle order using the IRAF FXCOR package. In all cases except for the third Ca triplet line for the faintest UMa star, we obtained a clear cross-correlation function peak.

A potential problem with single-slit observations is that mis-centering of the star on the slit will produce a velocity offset common to all orders. To address this problem, we note that telluric absorption lines experience the same spurious velocity shift as stellar absorption lines, and can be used to adjust the velocity back to its correct value. Accordingly, we computed a velocity adjustment using telluric absorption features around 6880 Å. Using a template created from the telluric lines from

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one of the bright standard stars, we used cross-correlation to compute relative velocity adjustments of the other stars. In all cases, the adjustment was less than 0.8 km s\(^{-1}\).

An additional potential source of inaccuracy is template mismatch; for instance, the H\(\alpha\) line is actually a blend of several different transitions, and may not be exactly at the template wavelength. To address this problem, we adjusted all of the velocities for each stellar line en masse relative to the second Ca line by computing the median velocity difference between the line and the second Ca line. This procedure introduced a shift of at most 1.6 km s\(^{-1}\).

Next, we treated each velocity for each stellar line as an independent measurement, and combined them to obtain a final velocity and error. Finally, we shifted the entire velocity set to bring the standards into agreement with their published velocities, with a final scatter of 0.4 km s\(^{-1}\), slightly larger then the intrinsic standard star uncertainty of 0.3 km s\(^{-1}\). For each star, we obtained two error estimates: \(\sigma_{\text{IRAF}}\), obtained by rescaling the nominal IRAF FXCOR velocity errors to give the expected \(x^2\); and \(\sigma_{\text{scat}}\), obtained from the empirical velocity scatter among individual lines. For UMa stars, the two errors are generally similar, but \(\sigma_{\text{IRAF}}\) apparently overestimates the errors for the bright standard stars. Table 1 shows the results for our seven target stars.

In Figure 2, we show the velocities as a function of magnitude. Objects 3 and 4 are clearly outliers, separated about 60 km s\(^{-1}\) from the other five objects.

The equivalent width of the Ca triplet can be used as a measure of a star’s metallicity, for known surface gravity (dwarf vs. giant) (e.g., Armandroff & Da Costa 1991). To establish whether the kinematical outliers are members of the UMa population, we computed the equivalent width of the Ca triplet lines by fitting them with a Lorentzian profile plus a linear continuum, and then integrating the difference between the line profile fit and the continuum fit. We compute the uncertainties of the equivalent widths using a Monte Carlo procedure: we generated simulated data using our best fit solution added to the empirical noise spectrum output by the MAKEE reduction package, and fit the simulated data in the same manner as the real data.

Figure 3 shows the equivalent widths for the three Ca lines.

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**TABLE 1**

| Object | R.A. (J2000.0) | Decl. (J2000.0) | g | i | v | \(\sigma_{\text{IRAF}}\) | \(\sigma_{\text{scat}}\) |
|--------|----------------|----------------|---|---|---|----------------|----------------|
| 1 ...... | 10 35 28.51 | +51 57 00.9 | 18.64 | 17.45 | -54.87 | 1.00 | 1.30 |
| 2 ...... | 10 34 30.51 | +51 57 07.0 | 18.88 | 17.75 | -50.80 | 0.96 | 1.09 |
| 3 ...... | 10 35 15.87 | +51 59 32.0 | 18.93 | 17.82 | 15.12 | 1.45 | 0.94 |
| 4 ...... | 10 34 52.44 | +51 57 02.2 | 19.08 | 17.89 | 8.21 | 1.50 | 0.40 |
| 5 ...... | 10 34 52.05 | +51 58 28.3 | 19.29 | 18.25 | -64.22 | 1.90 | 0.65 |
| 6 ...... | 10 34 42.36 | +51 58 06.1 | 19.45 | 18.37 | -38.95 | 1.80 | 1.25 |
| 7 ...... | 10 35 17.23 | +51 55 33.7 | 19.48 | 18.38 | -53.53 | 5.00 | 5.15 |

**Notes.**—First column is an object identification number. Cols. (2) and (3) are the position in J2000.0 coordinates. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Cols. (4) and (5) are the SDSS g and i magnitudes. Cols. (6), (7), and (8) are v, the measured heliocentric velocity; \(\sigma_{\text{IRAF}}\), the uncertainty obtained from the rescaled IRAF FXCOR velocity error; and \(\sigma_{\text{scat}}\), the uncertainty obtained from the velocity scatter among the different absorption lines.
9.3 km s$^{-1}$, the systemic heliocentric velocity of UMa is $-52.5 \pm 4.3$ km s$^{-1}$.

4. MASS-TO-LIGHT RATIO

The central mass-to-light ratio of a stellar system with an isotropic orbital distribution and constant $M/L$ can be expressed as $(M/L)_s = 9\eta (v^2)/[2\pi G \rho S_h]$, where $\eta$ is a luminosity distribution–dependent factor always close to 1, $r_h$ is the half-brightness radius, and $S_h$ is the surface brightness (Richstone & Tremaine 1986). Using UMa’s approximate published total luminosity $M_\odot = -6.75 (L_V \sim 4 \times 10^4 L_\odot)$ and half-light radius $r_{1/2} = 250$ pc (Willman et al. 2005), we obtain a central surface brightness of $S_h = 0.11 L_\odot$ pc$^{-2}$. Assuming that $(v^2)^{1/2} = 9.3$, one then obtains $(M/L)_s \approx 550 M_\odot/L_\odot$, as one might expect for a system that is nearly an order of magnitude fainter than known dark-matter-dominated dSphs, but has the same dispersion. The central density is then $\rho_0 = 0.18 M_\odot$ pc$^{-3}$ = 6.8 GeV cm$^{-3}$ using the above equation, or $\rho_0 = 0.22 M_\odot$ pc$^{-3}$ using the formula $\rho_0 = 166(v^2)_{v=0}$ (Mateo 1998). Despite UMa’s extreme $M/L$, its density is within a factor of 2 of that of several other dSphs (Mateo 1998). Several important caveats apply, however. First, we have identified the half-light radius with the half-brightness radius, when in truth they differ. If UMa has a Plummer profile, for example, then $r_h = 0.64r_{1/2}$, and we underestimate $M/L$ substantially. Next, the above formula for $\rho_0(r_h)$ strictly applies only to systems with constant $M/L$, whereas a dwarf with a halo has varying $M/L$, a fact that is often ignored when computing $M/L$ using core fitting. Thus, the above values of $(M/L)_s$ and $\rho_0$ are intrinsically imprecise and are useful primarily as relative values to compare with other dSphs having similarly computed qualities.

An alternative approach to computing the mass of the system is the projected mass estimator (Bahcall & Tremaine 1981; Heisler et al. 1985; Evans et al. 2003), whereby the mass of a system with $N$ measured radial velocities $v_i$ at projected radii $R_i$ is given by $M = [C (GN)] \Sigma_{i=1}^N v_i R_i$, where $C$ is a constant depending on the mass and light distributions of the system. For our five-member UMa data, this becomes $M = C (1.5 \times 10^4) M_\odot$. Evans et al. (2003) compute $C$ for the general case of measuring the mass between radii $r_{\min}$ and $r_{\max}$ for a $\rho \propto r^{-\alpha}$ tracer population in a $\phi \propto r^{-\beta}$ potential. Taking $r_{\min} = 100$ pc from our innermost star, assuming that all the stars are within the half-light radius so that $r_{\max} = 250$ pc, and further assuming that $\gamma = 3$, with a halo having a flat rotation curve ($\alpha = 0$), we obtain $C \approx 6$, again giving $M \approx 10^7 M_\odot$ and $M/L \sim 500$ inside the region observed. The mass varies from $5 \times 10^5$ to $2 \times 10^7 M_\odot$ as $\gamma$ ranges from 2 to 6.

We further note that dSphs for which radially extended data exist have a mean $M/L$ within the apparent stellar cutoff or “tidal” radius that is nearly an order of magnitude larger than the core-fit central $M/L$ (e.g., compare Mateo [1998] with Kleya et al. [2001], Wilkinson et al. [2004], and Kleya et al. [2004]). If we accept the CDM result that halos are similar in structure, then UMa might have a global $M/L \sim 3000 M_\odot/L_\odot$.

5. DISCUSSION

Our stellar velocity measurements show that UMa is a nearly dark, low-mass halo, almost an order of magnitude less luminous than previously known dSph galaxies of similar mass. We obtain a central mass-to-light ratio $M/L \sim 500 M_\odot/L_\odot$. Hence, UMa may have a mean $M/L \sim 3000 M_\odot/L_\odot$. If this extrapolates to larger radii like other dSphs, UMa may have a mean $M/L \sim 5000 M_\odot/L_\odot$. However, UMa may be the most dark matter dominated galaxy yet discovered. For comparison, the recently discovered $10^{11} M_\odot$ VIRGOHI 21 H 1

Fig. 3.—Equivalent widths of the three calcium triplet lines. The redder two lines of objects 3 and 4, which are apparent nonmembers on the basis of velocity, also have a significantly larger equivalent width than the other stars. The equivalent widths for object 7 are more uncertain than the error bars indicate because the absorption lines were almost invisible to the eye, and the fits may be entirely spurious. No fit could be obtained for the reddest line of object 7.

The kinematical outliers 3 and 4 clearly have a larger equivalent width for the second and third Ca lines, although the first line shows no difference. Object 7 produces very poor fits because the lines are barely discernible above the noise, and its equivalent widths are highly suspect. Generally, only the second and third lines are used for metallicity determination (Armoldoff & Da Costa 1991), so the absence of an effect for the weaker first line is not a source of concern. However, for a fixed metallicity, the equivalent width is antecorrelated with magnitude with a slope about 0.6 $\text{mag}^{-1}$ (Armoldoff & Da Costa 1991), so that it appears anomalous that star 6 has a larger equivalent width than the brighter stars 1, 2, and 5. To be cautious, we consider the possibility that both 6 and 7 are nonmembers.

3. VELOCITY DISPERSION AND SYSTEMIC VELOCITY

The simple rms line of sight dispersion of the five member objects (1, 2, 5, 6, and 7) is 9.1 km s$^{-1}$, and if we omit both 6 and 7, then $v_{\text{rms}} = 4.7$ km s$^{-1}$. These three cases, in the same order, we are confident with 95% certainty that the dispersion is greater than 6.5, 7.3, and 4.7 km s$^{-1}$.

Assuming five genuine members with a true dispersion of
source has $M/L > 500 \frac{M_\odot}{L_\odot}$ (Minchin et al. 2005), and the extreme dark spiral NGC 2915 has $M/L \approx 80$ (Meurer et al. 1996).

The CDM structure formation paradigm predicts that dark matter clumps into cusp halos characterized by a single parameter, the central density, with the smallest and least massive halos being the densest (Navarro et al. 1997). Problematically, CDM also predicts an order of magnitude more small Galactic satellite halos than are actually observed (e.g., Klypin et al. 1999), but it is unclear whether the theory is at fault, or whether the missing halos are too dark to be observed.

High-velocity clouds (HVCs) have been suggested as candidates for the missing CDM dwarf halos (Blitz et al. 1999). This suggestion remains controversial, especially as the high velocity clouds may themselves be divided into compact and diffuse subclasses with possibly different origins (e.g., de Heij et al. 2002). There is no clear distance determinant for the HVCs around the Milky Way, and, for a long time, there was no clear consensus as to whether the HVCs were Galactic or extragalactic. This ambiguity may have been resolved by the detection of a faint circumsolar HVC population around the Andromeda galaxy (M31) by Thilker et al. (2004), who argue that the available data are consistent with formation mechanisms via cooling flows, with tidal debris from mergers, or with gaseous counterparts of the missing CDM halos.

Accordingly, UMa may represent the best candidate for a “missing” CDM halo. Its existence raises several interesting questions.

**Why do the dSphs have a similar velocity dispersion, a similar central density, and, presumably, a similar mass, as noted by Mateo et al. (1998)?** It is curious that Draco, UMi, and UMa, the three lowest luminosity Galactic dSphs, all have the same dispersion, about $(\langle v^2 \rangle)^{1/2} = 10$ km s$^{-1}$, and And IX, the second-faintest known dSph, has $(\langle v^2 \rangle)^{1/2} = 6.8^{+3.0}_{-2.0}$ (Chapman et al. 2005).

Is there a minimum halo size in which stars can form, or a minimum clustering scale for the dark matter? There was no survivability reason why UMa could not have been much less massive. For instance, the mass required to bind a 500 pc dwarf halo against tidal disruption by a $10^{-12} M_\odot$ Galaxy at UMa’s distance of 100 kpc is estimated by equating the dwarf and Galactic densities, so that $M_{\text{crit}} \sim (10^{-12} M_\odot) (500 \text{ pc}/100 \text{ kpc})^3 \sim 10^{-5} M_\odot$, or about 2 orders of magnitude less massive than UMa’s central region and perhaps 3 orders of magnitude less massive than its global mass.

Kormendy & Freeman (2004) have compiled scaling relations among dwarf galaxies and more massive ellipticals, relating $M_B$, $v_\text{circ}$, and $(\langle v^2 \rangle)^{1/2}$. We can locate UMa in this ensemble, using the values $p_0 = 0.18 M_\odot$ pc$^{-3}$, $(\langle v^2 \rangle)^{1/2} = 9.3$ km s$^{-1}$, $v_\text{circ} \sim r_{1/2} \sim 250$ pc, and $M_B = M_v + 0.9 = -5.65$, where $M_v = -6.75$ has been converted to $B$ band using the typical $B - V \approx 0.9$ color of a K giant. From Figures 2 and 4 of Kormendy & Freeman (2004), we find, unsurprisingly, that UMa is typical of the dSphs in all respects but luminosity. All but two of the previously known dSphs and dIrrs fall onto a tight Faber-Jackson relation between velocity dispersion and luminosity, albeit with a systematic offset relative to larger ellipticals. UMi and Dra are the exceptions, being about 3 mag underluminous for their mass. To agree with the general trend, UMa would need to have a dispersion of $< 3$ km s$^{-1}$, or would have to be about 5 mag brighter.

It has been suggested that the dSphs’ extreme $M/L$ results from the expulsion of baryons from their shallow potential well by supernovae (Larson 1974; Dekel & Silk 1986). Because the potential wells of the dSphs seem comparable, UMa must have been intrinsically baryon poor to begin with, or else the baryon expulsion efficiency must have varied by 1 or 2 orders of magnitude among dSphs in order to produce their very different luminosities. UMa demonstrates that the luminosity scatter at the low-mass end of the galaxy distribution is very large. It appears likely that more dark and massive dwarfs are lurking in the vicinity of the Galaxy. Detections of more candidate objects are urgently needed to check whether the number and properties of the population are truly consistent with the missing dark matter halos of the simulations.

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