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KINEMATICALLY COLD POPULATIONS AT LARGE RADII IN THE DRACO AND URSA MINOR DWARF SPHEROIDAL GALAXIES

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ABSTRACT

We present projected velocity dispersion profiles for the Draco and Ursa Minor (UMi) dwarf spheroidal galaxies based on 207 and 162 discrete stellar velocities, respectively. Both profiles show a sharp decline in the velocity dispersion outside ∼30′ (Draco) and ∼40′ (UMi). New deep photometry of Draco reveals a break in the light profile at ∼25′. These data imply the existence of a kinematically cold population in the outer parts of both galaxies. Possible explanations of both the photometric and the kinematic data in terms of both equilibrium and nonequilibrium models are discussed in detail. We conclude that these data challenge the picture of dwarf spheroidal galaxies as simple, isolated stellar systems.

Subject headings: dark matter — galaxies: individual (Draco dwarf spheroidal, Ursa Minor dwarf spheroidal) — galaxies: kinematics and dynamics — Local Group — stellar dynamics

1. INTRODUCTION

The dark matter–dominated Local Group dwarf spheroidal galaxies (dSph's) have emerged as valuable laboratories in which to test dark matter models. Recently, the projected velocity dispersion profiles of the Fornax and Draco dSph's have been obtained (Mateo 1997; Kleyna et al. 2001). Detailed modeling of the discrete stellar velocities in Draco enabled the hypothesis that mass follows light to be discarded at the 2.5 σ level and suggested that the halo density $\rho(r)$ falls off more slowly than the light distribution with $\rho(r) \sim r^{-1.7}$ (Kleyna et al. 2002). In this Letter, we present new observations of the Draco and Ursa Minor (UMi) dSph's that yield the velocity dispersion profiles of both galaxies to the edge of their light distributions. The new data suggest the existence of kinematically cold populations in the outer parts of both galaxies. These data make it possible to test the validity of isolated equilibrium models of dSph's.

2. OBSERVATIONS

2.1. *Discrete Velocities*

We observed the Draco and UMi dSph's with the multifiber instrument AF2/Wide-Field Fiber Optics Spectrograph (WYFFOS) on the William Herschel Telescope on La Palma on 2003 June 20–23 and 2003 May 6–11, respectively. We drew our Draco targets from the Sloan Digital Sky Survey, while we took our UMi targets from our own KPNO 4 m MOSAIC imaging. In each case, we identified potential targets by drawing a polygon around the giant branch of a V, $V-I$ color-magnitude diagram with a faint magnitude limit of $V<20$. The data were reduced using the WYFFOS-specific WYFRED data reduction package in IRAF and cross-correlated with the two bluemost lines of the Calcium triplet, in the same manner as described by Kleyna et al. (2002). To determine the final member list for each dSph we assumed that their velocity distribution was Gaussian with a dispersion (including measurement error) of $\lesssim 12.5$ km s^{-1}.

Our final Draco data set contains 112 velocities within 39 km s^{-1} of Draco's mean velocity with a median velocity error of 2.4 km s^{-1}. The union of these data with the data set of Kleyna et al. (2001) contains 207 unique members with good velocities. The median velocity of the combined data set is $-290.7^{+1.2}_{-0.6}$ km s^{-1}, where the uncertainties are obtained through bootstrap resampling. Our final UMi data set has 144 stars within 36 km s^{-1} of the mean velocity, with a median velocity error of 2.9 km s^{-1}. Adding the earlier UMi velocities of Kleyna et al. (2003) produces a data set with 162 member stars. The median velocity of the combined data set is $-245.2^{+1.0}_{-0.6}$ km s^{-1}.

For both Draco and UMi, at large radii the individual velocities of the stars relative to the mean tend to decline with increasing distance from the center. In the case of UMi, this is particularly striking with six of the seven outermost stars lying within 1 σ of the mean bulk velocity of the dSph. Figure 1 shows the radial variation of the line-of-sight velocity dispersion σ_P in Draco and UMi. The projected dispersion drops sharply at large radii. In each dSph, we detect no rotation beyond that identified in previous work. Since our selection criterion for dSph membership is based on the assumption of a Gaussian velocity distribution, we would expect to discard less than one genuine member in Draco (UMi) by imposing a 39 km s^{-1} (36 km s^{-1}) cutoff with the possible exception of extreme binaries. The presence of some outliers just inside the velocity cutoff at large radii suggests that we may, in fact, be retaining some nonmembers in our sample. If 3% of our data belong to the Galactic foreground (assumed to have a flat velocity distribution between our velocity limits), then the overall dispersion of our sample would be increased by about 1 km s^{-1}. Thus, nonmember contamination at large radii would tend to strengthen our conclusion of a falling velocity dispersion. It could be invalidated only if we had erroneously removed large-velocity bound stars from the sample.

2.2. *Photometry*

Figure 2 shows the azimuthally averaged surface brightness profile of Draco based on deep imaging to $V\approx 25$ and $i'\approx 24$ with the Isaac Newton Telescope. This has been corrected

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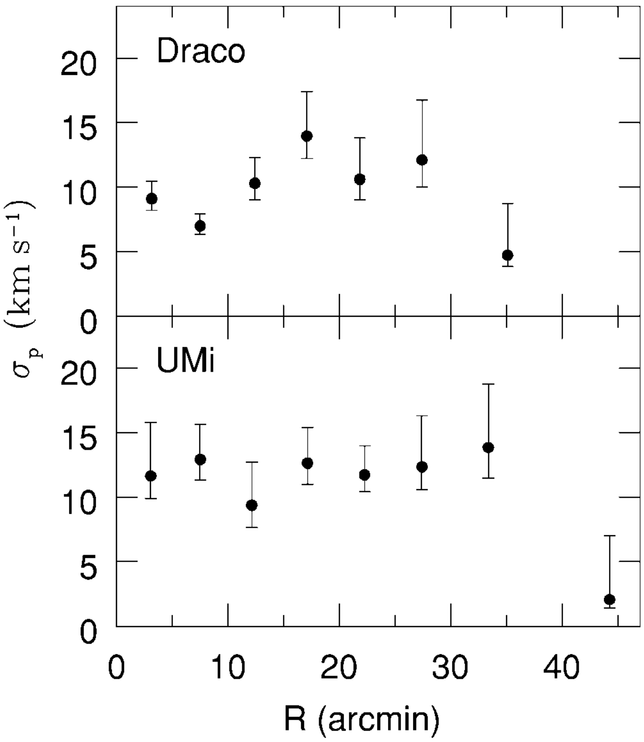

FIG. 1.—Line-of-sight velocity dispersion profiles (with 1 σ error bars) for Draco and UMi. See text for a detailed discussion.

for the effects of variable extinction using the reddening map of Schlegel et al. (1998). The limiting magnitude of our observations is about 2 mag fainter than that of the Sloan Digital Sky Survey data used by Odenkirchen et al. (2001) to determine the light profile of Draco and permits more robust background subtraction in the outer regions. In contrast to the Odenkirchen et al. photometry, the profile in Figure 2 shows a clear break at $\sim 25'$. We note that a similar result has been recently claimed by Kuhn et al. (2004). The light profile of UMi displays a similar feature (e.g., Irwin & Hatzidimitriou 1995; Palma et al. 2003; Martínez-Delgado et al. 2001) at about $34'$. This militates against the idea that the dSph's currently possess extended halos (e.g. Stoehr et al. 2002).

Using simulations, Johnston et al. (1999, hereafter J99) suggested that stellar systems in the Milky Way halo will show breaks in their surface density profiles, beyond which unbound or extratidal stars begin to predominate over bound stars. Their results are superficially similar to our photometric data on Draco and UMi, but there are some important differences. First, J99 found an enhanced velocity dispersion due to the extratidal stars, and second, they argued for a slow falloff (proportional to R^{-1}) in surface brightness beyond the break. Johnston et al. (2002) considered noncircular dSph orbits and found a wide variety of profile shapes and outer falloff rates, with milder breaks and steeper falloffs occurring around the apocenters of more eccentric orbits. They also found that the ratio of the break radius to the actual tidal radius varies with orbital phase and eccentricity and is significantly below unity near apocenter.

Also shown in Figure 2 are the best-fitting King (1962) and Plummer profiles for the surface brightness profile of Draco. The former fits the inner parts well but requires an additional extratidal population at $R > 25'$ to mimic the break. The latter provides a reasonable description of the entire profile. In the rest of this

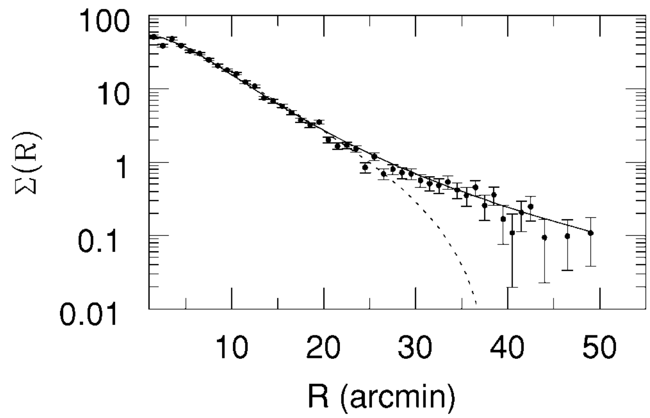

FIG. 2.—Azimuthally averaged surface brightness profile of Draco. The solid and dashed curves show, respectively, the best-fitting Plummer profile and a King (1962) profile fit to the data within $25'$.

Letter, we use these models to try to understand the surprising data on the velocity dispersions of Draco and UMi.

3. MODELING

3.1. *Equilibrium Models*

Using the simplifying assumptions of virial equilibrium and spherical symmetry, the observable line-of-sight velocity dispersion σ_P as a function of projected radius R is

$$\sigma_P^2(R) = \frac{2}{I(R)} \int_R^\infty dr\, \nu(r) f(r) \frac{GM(r)}{r} \times \int_R^r dw\, \frac{w}{f(w)\sqrt{w^2 - R^2}} \left[1 - \beta(w)\frac{R^2}{w^2}\right], \quad (1)$$

where $I(R)$ is the surface brightness and $\nu(r)$ is the stellar luminosity density. This expression also involves the mass profile $M(r)$ of the dark matter halo and the stellar velocity anisotropy parameter $\beta(r) = 1 - \langle v_\theta^2 \rangle / \langle v_r^2 \rangle$. The function $f(r)$ is the integrating factor for the spherical Jeans equation, namely, $\exp\,[-\int_0^r dr\, 2\beta(r)/r]$.

Under the assumption of isotropy ($\beta = 0$), equation (1) becomes an Abel integral equation, which can be inverted to give the mass profile $M(r)$ of the dark matter halo (Binney & Tremaine 1987, § 4.2). Using an analytic fit to Draco's projected dispersion together with either a Plummer or a King profile in the Abel inversion, we find that the cumulative mass $M(r)$ becomes unphysical ($dM/dr < 0$) beyond $r \sim 30'$. An isotropic model with a Plummer or King profile cannot reproduce the observed sharp decline in σ_P for Draco. Analogous fits to the dispersion profile and luminosity density of UMi lead to a similar conclusion for its mass profile at the radius where its velocity dispersion falls.

3.1.1. *A Sharp Change in the Velocity Anisotropy?*

One possibility is that the velocity anisotropy changes abruptly from isotropy ($\beta = 0$) in the inner parts to strong radial anisotropy ($\beta \to 1$) in the outer parts. This could cause a sharp drop in the projected dispersion, even if the stellar density and dark matter profile vary slowly and smoothly. We have investigated this option using equation (1) together with an anisotropy parameter $\beta(r) = r^n/(r^n + r_a^n)$, which tends to a

Heaviside function $H(r_a)$ about the anisotropy radius r_a as $n \to \infty$. Figure 3 shows the projected velocity dispersion σ_P assuming a Plummer model for the dSph luminosity density. The halo is a "parabolic velocity curve" model as advocated by Stoehr (2004) as an excellent fit to subhalos in high-resolution simulations of the Milky Way halo. The observable dispersion is computed under the assumption of isotropy or extreme tangential or radial anisotropy together with the Heaviside step-function anisotropy. A very sharp change in anisotropy can cause σ_P to fall at $R \sim r_a$. In fact, for a stellar population with luminosity density $\nu \propto r^{-n}$ in a dark halo with an underlying rotation curve behaving like $V(r) \sim r^{-\gamma}$, σ_P falls by a factor of $1/(n + 2\gamma - 2)^{1/2}$ after a sudden change to radial anisotropy.

For Draco, a smooth Plummer profile provides a reasonable fit to the stellar density. Given the large error bar on the outermost data point of the velocity dispersion, a sudden change in the anisotropy at large radii could plausibly explain the data. For UMi, however, the outermost dispersion data point is better constrained and the photometry is less well represented by a smooth profile. A sharp change in the anisotropy cannot by itself produce the drop in σ_P, unless the stellar density or the dark halo also changes at the anisotropy radius r_a.

3.1.2. *A Sharp Edge in the Light Distribution?*

If a dSph has a sharp edge in its light distribution, then σ_P would necessarily fall to zero at projected radii approaching that edge. Let us suppose that as $r \to r_t$, the stellar density behaves like $\rho \sim (r_t - r)^n$. Then, by expanding equation (1), it can be shown that

$$\sigma_P \sim C(r_t - R)^{1/2} R^{-(1+\gamma)/2}. \quad (2)$$

The anisotropy β and the falloff in the stellar density n alter the constant C but not the scaling with distance from the edge r_t. The dark halo has been assumed to possess an underlying rotation curve behaving like $V(r) \sim r^{-\gamma}$, so that the case $\gamma = \frac{1}{2}$ (Keplerian rotation) corresponds to truncation of the dark halo. So, irrespective of whether the dark halo is extended or truncated, the velocity dispersion of the dSph must always go to zero like $(R - r_t)^{1/2}$, if the stellar distribution has a sharp edge.

For both Draco and UMi, a sharp edge to the stellar distribution seems at first sight inconsistent with the photometry. However, as the overplotted King profile in Figure 2 shows, we can associate a tidally limited model with Draco provided that the excess of stars at $R \gtrsim 25'$ is interpreted as an extratidal (and possibly unbound) population. If so, it is surprising that the extratidal stars are kinematically colder than those in the main body of Draco. This situation admits two possible explanations. First, the tails could be kinematically cold, either intrinsically or because of projection effects. This is not out of the question, as discussed later in § 3.2. Here, we merely note that Liouville's theorem tells us that phase-space density is conserved in the absence of mixing, so that a stretching of material to form a tidal tail must be accompanied by a corresponding contraction in velocity space. Second, given the small numbers involved, is it possible that we have missed stars associated with the extratidal enhancement? This seems unlikely, as the density in the tails is higher than that of Draco at the radii sampled by our outer velocity bin. However, the presence of age or metallicity gradients could potentially lead us to sample preferentially one population in the outer parts; our Draco photometric data provide some evidence that the blue and red horizontal branches have different spatial distributions (see also Klessen et al. 2003). In the case of UMi, the narrowness of the red giant branch (RGB) makes it more difficult to miss a dominant tail population in the outer parts; the weak age gradients identified by Carrera et al. (2002) do not manifest themselves in the RGB. One might also worry that the geometry of our WYFFOS pointings in UMi might miss the areas dominated by the extratidal population. In fact, our outer pointings were aligned with the major axis of the stellar distribution and completely sample the elliptical region with a semimajor axis of 50′.

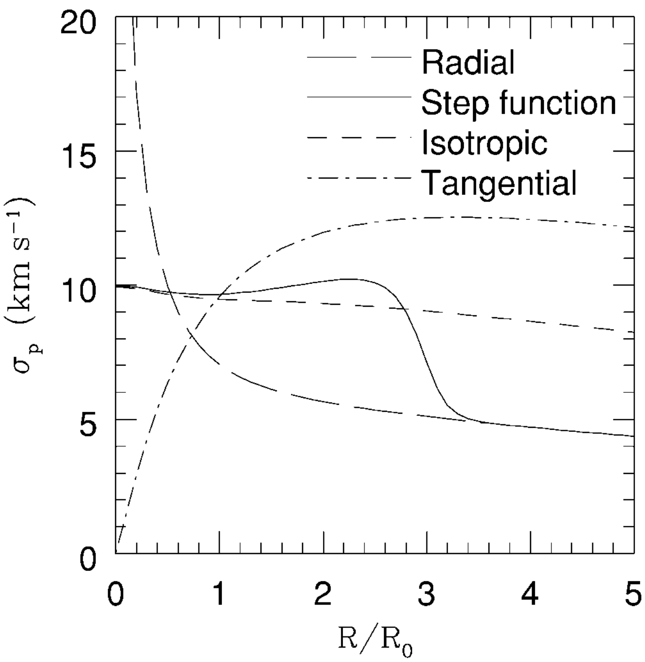

FIG. 3.—Projected velocity dispersion for a Plummer light profile (scale length R_0) in a dark matter halo assuming four different velocity anisotropy laws. Even an extremely sharp change in the velocity anisotropy does not reproduce the decrease in velocity dispersion seen in UMi.

3.1.3. *Two-population Models for dSph's?*

It is worth considering whether Draco and UMi might contain two kinematic populations: a hot, inner "bulgelike" component surrounded by either a "disk" or a "halo" component. One objection to this model is that populations with different spatial distributions must have formed under different conditions and would therefore not be expected to display such similar stellar populations. However, it is possible that the weak age gradients seen in UMi and the differences in the spatial distributions of blue and red horizontal branch stars in Draco indicate the presence of more than one old population (see, e.g., Harbeck et al. 2001).

The low projected velocity dispersion in the outer parts of both Draco and UMi would appear to be consistent with the vertical velocity dispersion of a thin disk. However, in each case the absence of an observed rotation signal across the face of the dSph implies that we must be observing the disk approximately face-on. For the line-of-sight component of rotation to be smaller than our velocity errors, any disk would have to be aligned to within 6° of face-on. This is in contradiction with the observed flattening of UMi, which suggests that any disk must be close to edge-on. A pressure-supported halo population might be a more plausible candidate for the extratidal population. In Draco, the isopleths of the stellar density distribution suggest that the extratidal population within about 50′ has the same symmetry as the main body of the dSph. However, the observed kinematics require that both populations be truncated in order to give projected dispersions for each population that fall rapidly in the outer parts. For UMi, this model suffers from the additional difficulty of the significant flattening required for both populations. If this is produced by anisotropy in the velocity distribution (rather than by the effects of external tides), it is at the extreme end of the range normally seen for flattened systems without rotation.

3.2. *Tidal Sculpting of Draco and UMi?*

A natural explanation for a break in the light distribution of a Local Group dSph is to invoke the external tidal field produced by the Milky Way. This perturbs the outer regions of all Galactic satellites leading to the escape of stars and the formation of tidal tails (e.g., J99). However, in the case of Draco and UMi there are two problems associated with this simple scenario. First, for Draco our mass estimate interior to the break radius in the light is $1 \times 10^8\ M_\odot$, while for UMi it is $2 \times 10^8\ M_\odot$. Flattening of the gravitational potential and velocity anisotropy causes uncertainty in these masses by a factor of ∼2. Both dSph's seem sufficiently massive that, given any reasonable assumed Milky Way halo profile, their current tidal radii lie outside the observed light distribution. This suggests that neither Draco nor UMi is currently experiencing tidal disturbance of its stellar distribution. Second, tidal effects typically result in the heating of stellar populations, and therefore the velocity dispersion of the dSph's is expected to rise in the region that has been influenced by tides, in stark contrast to the observed data.

The difficulties might be resolvable if the Galactic orbits of Draco and UMi are significantly elongated with pericenters smaller than 20 kpc. For Draco, such an orbit is not inconsistent with the observed space motion due to the large uncertainties on the measured proper motion. The proper motion of UMi is currently better constrained (Schweitzer et al. 1997) and appears to rule out a deeply plunging orbit. However, a preliminary measurement of the proper motion based on *Hubble Space Telescope* data with a 4 year baseline is consistent with an elongated orbit (S. Piatek 2004, private communication). During pericenter passages, the tidal radii of the dSph's are smaller than at their present locations. If a dSph passes close to the disk of the Milky Way, then the rapidly time-varying gravitational field disturbs its outer parts. This generates a heated population of stars at the edge of the dSph with an inflated velocity dispersion. If the orbit is further constrained to have a pericenter passage after the mild disk shock, then the heated extratidal population can drift away from the dSph. Subsequently, as the dSph moves out to its current location, the tidal radius increases again, and the colder stars in the tidal tails that have not had sufficient time to escape during the pericenter passage are recaptured. This results in a population that has the morphological appearance of a tidal tail but is kinematically cold. It is also possible that the cold clump near the center of UMi (Kleyna et al. 2003) is a projection of this cold extratidal population onto the face of the dSph.

This scenario places rather tight constraints on the properties of both Draco and UMi as well as on their possible Galactocentric orbits. First, their orbits must take them within 20 kpc of the Milky Way. Second, a simple estimate of their tidal radii (following, e.g., Kleyna et al. 2001) shows that even at this radius their tidal limits are large with respect to their stellar populations unless their masses are below $5 \times 10^7\ M_\odot$, which is at the lower limit allowed by the data. Third, their orbits must spend sufficient time near pericenter to allow the stars that have been most heated during the close passage to escape before the sphere of influence of the dSph engulfs them. We conclude that this scenario is plausible only if Draco and UMi have somewhat lower masses than previously estimated and have a low dark matter density outside about 30′. Furthermore, both dSph's must be on deeply plunging orbits that take them close to the disk of the Milky Way. We are currently performing *N*-body simulations to investigate this scenario in more detail.

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REFERENCES

Binney, J., & Tremaine, S. 1987, Galactic Dynamics (Princeton: Princeton Univ. Press)
Carrera, R., Aparicio, A., Martínez-Delgado, D., & Alonso-García, J. 2002, AJ, 123, 3199
Harbeck, D., et al. 2001, AJ, 122, 3092
Irwin, M., & Hatzidimitriou, D. 1995, MNRAS, 277, 1354
Johnston, K. V., Choi, P. I., & Guhathakurta, P. 2002, AJ, 124, 127
Johnston, K. V., Sigurdsson, S., & Hernquist, L. 1999, MNRAS, 302, 771 (J99)
King, I. 1962, AJ, 67, 471
Klessen, R. S., Grebel, E. K., & Harbeck, D. 2003, ApJ, 589, 798
Kleyna, J. T., Wilkinson, M. I., Evans, N. W., & Gilmore, G. 2001, ApJ, 563, L115
Kleyna, J. T., Wilkinson, M. I., Evans, N. W., Gilmore, G., & Frayn, C. 2002, MNRAS, 330, 792
Kleyna, J. T., Wilkinson, M. I., Gilmore, G., & Evans, N. W. 2003, ApJ, 588, L21
Kuhn, J. R., Kocevski, D., & Fleck, J.-J. 2004, in Satellites and Tidal Streams, ed. F. Prada & D. Martinez-Delgado (San Francisco: ASP), in press (astro-ph/0309207)
Martínez-Delgado, D., Alonso-García, J., Aparicio, A., & Gomez-Flechoso, M. A. 2001, ApJ, 549, L63
Mateo, M. 1997, in ASP Conf. Ser. 116, The Nature of Elliptical Galaxies, ed. M. Arnaboldi, G. S. Da Costa, & P. Saha (San Francisco: ASP), 259
Odenkirchen, M., et al. 2001, AJ, 122, 2538
Palma, C., Majewski, S., Siegel, M. H., Patterson, R. J., Ostheimer, J. C., & Link, R. 2003, AJ, 125, 1352
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Schweitzer, A. E., Cudworth, K. M., & Majewski, S. R. 1997, in ASP Conf. Ser. 127, Proper Motions and Galactic Astronomy, ed. R. M. Humphreys (San Francisco: ASP), 103
Stoehr, F. 2004, MNRAS, submitted (astro-ph/0403077)
Stoehr, F., White, S. D. M., Tormen, G., & Springel, V. 2002, MNRAS, 335, L84