Internal Kinematics of Dwarf Spheroidal Galaxies

Edward W. Olszewski

Steward Observatory, University of Arizona, Tucson, AZ, 85721-0065

Abstract. We discuss the quality of kinematic data in dwarf spheroidal galaxies, the current interpretations of those data, and prospects for actually deriving the mass profile in these galaxies. We then discuss stellar populations constraints on some of the models that attempt to explain the kinematics and formation of the dSph’s.

1. Introduction

It has now been fifteen years since Marc Aaronson (1983) used the MMT echelle spectrograph to show that the CH stars in the Draco dwarf spheroidal (dSph) had velocities inconsistent with being drawn from a galaxy with luminosity $M_V = -8.5$ and with $M/L = 2$, which is the expectation for globular-cluster-aged population. Instrumentation and detectors have improved markedly in that time, allowing superb velocities to be obtained for stars in all of the dwarf spheroidals orbiting the Milky Way. The reader can find excellent reviews in Mateo (1994, 1998a,b), Da Costa (1998), and Pryor (1994).

2. The Velocities Themselves, Present and Future

In this section I will address the quality of the observational data. The conclusions will be that the central velocity dispersions of these galaxies are quite secure, and that the properties of the stellar populations being measured do not corrupt the line-of-sight velocities.

The typical star measured is a K giant. Fifteen years ago this was not the case. Legitimate questions were raised about atmospheric motions and a large binary population among the CH stars systematically inflating the measured velocity dispersion from the true one. K giants are rather well-behaved stars; for instance, Hatzes & Cochran (1996, 1993) find that pulsations in K giants occur at the 10–20 meter $s^{-1}$ level. Samples of 30–300 stars with individual velocity errors of 2–3 km $s^{-1}$ are now available for all of the Milky Way dSph’s.

The Ursa Minor and Draco galaxies, being the longest studied, have multi-epoch velocities for more than 50 stars. Table 3 of Olszewski et al. (1996a) shows that 41 stars have time baselines of 5 or more years, with seven monitored for 10 or more years. Olszewski et al. (1996a) and Hargreaves et al. (1996) have both shown that binary orbital motions do not inflate the measured dispersions above the true dispersions. Comparisons of the velocities in Ursa Minor measured by Armandroff et al. (1995) and Olszewski et al. (1995) and Hargreaves et al. (1994)
show that agreement is excellent, though with some low-level disagreements, finally negating the complaint of Lynden-Bell et al. (1983) that velocities did not agree within their quoted errors.

Ultimately one would like line-of-sight velocity distributions, which contain far more information than reducing all velocities to a single datum, the velocity dispersion. In the case of the Ursa Minor dwarf, which has one of the most extreme derived dark matter densities, perhaps as high as 1 M⊙ pc⁻³ (Pryor & Kormendy 1990), if we had all of the telescope time we needed, how well could we do? First, Ursa Minor is a highly resolved system, so long-slit spectra are out of the question. Second, to B~22, there are 4.0 stars arcmin⁻² (Irwin & Hatzidimitriou 1995, hereafter IH). To a radius of 1 core radius, which contains half of the stars in this system (UMi is very different from a globular cluster in this respect), there are 31 stars to V=18, 60 additional to V=19, 60 additional to V=19.5, and 100 additional to V=20 (Cudworth et al. 1986). Since UMi is nearby, (m−M)=19.1, and metal poor, the fainter giants and the subgiants are quite blue and weak lined, further adding to the observational difficulties. Samples of several hundred stars are going to be difficult to obtain. The Fornax and Sgr dSph’s are the only systems in which such large samples will be available. Each has its own problems: Fornax has a low heliocentric velocity, making samples unadulterated by Galactic foreground stars hard to obtain; Sgr is projected on a very crowded part of the Milky Way.

3. Tides

Given the published velocity dispersions and King-model fits to the projected density profiles, the dSph’s are dark-matter dominated in all cases (Mateo et al. 1993 and the reviews listed above). If the assumption that these systems are in equilibrium is true, then large central dark matter densities are needed and we have examples of the smallest systems known to contain dark matter. If the systems are out of equilibrium, then the large derived masses may be illusory.

Grillmair (1998) and Johnston (1998) discussed the tidal stripping of stars from stellar systems. Grillmair shows that globulars have lost most of their stars to tidal stripping, yet the derived M/L for globulars is “normal.” Simulations by Piatek & Pryor (1995) and by Oh et al. (1995) show that the central properties of dSph are little affected until the object is unrecognizable as a dSph. Finally, we have good evidence from its shape that Sgr is strongly affected by the Milky Way, yet its central velocity dispersion is, remarkably, the same as that of the much more distant (25 kpc versus 140 kpc) Fornax system, which is nearest to Sgr in luminosity (Ibata et al. 1997, Mateo et al. 1991). In fact, Ibata et al. (1997) argue that while Sgr is being stripped, the fact that it has survived at all means that it contains substantial dark matter.

Grillmair (1998), Piatek & Pryor (1995), and Oh et al. (1995) detail the evolution of a globular cluster or a dwarf spheroidal when acted upon, gently or strongly, by the Milky Way. Grillmair and Piatek & Pryor find that there are “signature plumes” from perigalactic passages. While these plumes are easily seen in the model, since they are of low surface brightness and since we do not know the true shapes or orientations of the dSph’s, the plumes are not easily seen in the density profiles. Piatek & Pryor stress that the clearest observed
signature would be ordered motions along the two plumes. A stellar sample would thus show a change in mean velocity along the major axis (see Fig 8 of Piatek & Pryor). Such a change is not observed in any dSph, except perhaps Sgr.

Kuhn & Miller (1989) claimed that resonances between internal pulsational timescales of a dSph and its orbital timescale about the Milky Way can produce departures from virial equilibrium and also produce large velocity dispersions. Pryor (1996) has raised a series of objections to this model, and Sellwood & Pryor (1998) have been unable to confirm this resonant pumping.

Klessen & Kroupa (1998, hereafter KK) and Kroupa (1997) have taken the point of view that there are circumstances in which no-dark-matter tidal tails can look remarkably like dSph’s. KK argue that if the orbit is of eccentricity \( >0.5 \), then, when you look along the orbit, the debris might look like a dSph. Furthermore, the ordered motions described above would mask themselves as an increase in the velocity dispersion, since all of the ordered motions would be along the line of sight. These models are testable in two ways: first, the true orbits can be derived from absolute proper motions. Second, since one is observing them along the direction of the tidal debris, one might expect that the color-magnitude diagram would show that the dSph’s all have large line of sight depths. KK’s Figure 18 shows predictions for the horizontal branch structure. We give constraints on this model in the final section.

4. Extra-Tidal Stars?

A departure of the dSph stellar density profile from that of the best-fitting King model does not automatically imply that extratidal stars have been detected. The long relaxation times in dSph’s mean that the velocity distribution is not necessarily Maxwellian. Given that the velocity dispersion profiles discussed below imply that mass does not follow light, at least two of King’s (1962) assumptions are violated. IH’s claim that there are extratidal stars is thus premature, as are conclusions drawn from such a claim (Moore 1996, Burkert 1997). In other studies, Gould et al. (1992) used deep multicolor photometry to find a few likely main-sequence stars at the distance of the Sextans dwarf. These stars are 100 arcmin from the center of Sextans, which at the time was thought to be beyond the tidal radius of Sextans. However, the most recent star counts (IH) have shown the tidal radius to be 160±50 arcmin. Kuhn et al. (1996) have claimed that 25% of the stars “in” Carina are outside its tidal radius. UMi would be a good confirming object, since it is less contaminated by foreground stars. Of course, as discussed above, significant mass loss does not imply that the measured velocity dispersions have been inflated.

5. Masses and Mass Profiles

The velocity dispersion profiles of \( \sim 100 \) stars in Draco, \( \sim 100 \) stars in UMi, and \( \sim 200 \) stars in Fornax tend to be rather flat, rather than to fall with increasing radius as a King model predicts. Models in which mass follows light are tightly constrained and seem to be ruled out by these data. There are two other reasons for preferring models in which mass does not follow light. First, profiles in which
mass does not follow light will provide the lowest central dark matter densities, which already seem rather high. Second, halos of dIrr and dwarf spiral galaxies are substantially bigger than the optical extents of dSph galaxies. Once we allow mass to be decoupled from light, it becomes much harder to pin down the mass profile (Merritt 1987).

The total masses of Draco and UMi can first be examined in a model-free way. Figure 1 shows the minimum global M/L needed to bind each star (Pryor et al. 1998). Applying single-component King models to these galaxies, Pryor & Kormendy (1990) calculate that the central-densities are $\rho_{\text{min}} \sim 1.0$ M$_\odot$ pc$^{-3}$ for Dra and UMi. The velocity dispersion profile discussed above is a poor fit to the predictions of the single-component models. The luminous central densities are $\sim 0.03$ M$_\odot$ pc$^{-3}$. Minimum masses derived from the virial theorem are $\sim 2.7 \times 10^7$ M$_\odot$, making M/L $\geq 10$. The new, larger set of velocities now available gives $\rho_{\text{min}} = 0.2$ M$_\odot$ pc$^{-3}$ for Draco and Umi (Pryor et al. 1998), using 2-component models described in Pryor & Kormendy (1990); achieving such low central densities is only possible with extended dark matter, thus these models have dark matter by definition.

Hans-Walter Rix has graciously run some models of Draco in which the input is the luminous matter profile and the velocity dispersion at three radii. Orbits are calculated for three different potentials, Keplerian, logarithmic (flat rotation curve), and harmonic (constant density), and populated such that the luminous density profile and velocity dispersion profile are matched (Figure 2). The $h_4$ parameter is a measure of departure from a Gaussian distribution, with negative $h_4$ having more stars in the velocity tails than does a Gaussian, and positive $h_4$ having more stars at the systemic velocity and fewer in the wings. The fourth row of panels shows the relative contribution of the tangential and radial dispersion profiles to the total dispersion, which will perhaps be a measurable constraint when internal proper motions are available for these systems (SIM and GAIA satellites).

Although the three $h_4$ profiles are different, with our current measuring errors (Armandroff et al. 1995), $h_4$ is constrained to $\pm 0.06$ for the global set of 90 stars, and to $\pm 0.13-0.15$ for two bins of 45 stars. Doubling the sample and

![Figure 1](image_url)
Figure 2. Numerical modelling of Draco by H.-W. Rix using Schwarzschild’s method (see Rix et al. 1997). Surface brightness profile of Draco taken from the literature (top panels); Derived velocity dispersion profile overlaid on the data (second row); $h_4$ statistic, the degree of departure from a Gaussian profile (third row); contribution of radial and tangential dispersions to the total velocity dispersion (fourth row); orbital weights (fifth row). Estimates of the observed $h_4$ in a 2-bin Draco sample are superposed on the $h_4$ plots.

lowering the measuring errors to 2–3 km s$^{-1}$ for every star will lower the errors in the $h_4$'s to a level that may allow these three models to be distinguished.

6. Stellar-populations Constraints to Models

KK’s models require a substantial orbital eccentricity. Schweitzer et al. (1995, 1998) have measured tangential velocities for UMi and Sculptor. Kyle Cudworth has graciously allowed me to quote their results: for UMi, $v_r = -86 \pm 1$, $v_t = 190 \pm 28$; for Scl, $v_r = 74 \pm 2$, $v_t = 210 \pm 125$. These results are in the Galactic rest frame. Cudworth estimates ratios of apogalacticon distance to perigalacticon distance of $\sim 2$ ($e = 0.3$). KK require large eccentricity and quote $e > 0.5$, or $r(\text{apo})/r(\text{peri}) > 3$, for their models to give large velocity dispersion. The more radial the orbit the better their model succeeds.

The velocity dispersions are not the only issue. Because such models are viewed along the orbit, there will be a nonnegligible line-of-sight depth. The
magnitude dispersion for 84 blue horizontal branch stars in Ursa Minor (Cudworth et al. 1986) is 0.09 mag. But 33 variables in M15 (Bingham et al. 1984) give a dispersion of 0.15 mag, and 35 variables in M3 (Sandage 1981) give a dispersion of 0.07 mag. The line of sight depth of UMi as measured by the horizontal branch is consistent with its projected size as measured from star counts.

The intriguing alignments of outer halo clusters and dSph’s on the sky (see Lynden-Bell & Lynden-Bell 1995 and Majewski 1994 for the latest papers on this subject) can be tested both by measuring orbits and by stellar populations arguments. The best stream in the opinion of Lynden-Bell and Lynden-Bell is LMC-SMC-UMi-Dra (with Sculptor and Carina as possible members). Umi is approximately 180° away in the sky from the Magellanic Clouds, so it must have been stripped long ago.

Ursa Minor and Draco are both as old as Galactic globulars (Olszewski & Aaronson 1985, Grillmair et al. 1998), and are very metal poor with [Fe/H]~−2 (Suntzeff et al. 1984, Lehnert et al. 1992, Shetrone 1998). UMi also has a blue horizontal-branch (HB) morphology (Cudworth et al. 1986).

The LMC has a ubiquitous red HB, with few, if any, BHB stars (see the references in the review of Olszewski et al. 1996b, and Geha et al. 1998 for examples). While the BHB of an old population is masked by the main-sequence of a younger one, there are other reasons to think that this old, metal-poor population is very small. First, there are remarkably few metal poor giant stars in a “halo” field defined by proper motions and complete spectroscopy (Olszewski 1993). This 0.25 deg² field, approximately 8 kpc from the center of the LMC, formed one giant star, or 3% of its mass as revealed by red giants, when it was as metal poor as the dSphs. Finally, the pulsational properties of the RR Lyraes imply evolution from a system with a red HB (Alcock et al. 1996). The mean abundance of the RR Lyraes is −1.3 to −1.8, again more metal rich than UMi or Dra.

There are few BHB stars in the SMC as well (Gardiner & Hatzidimitriou 1992). The mean age and abundance of the “halo” field near NGC 121 is 8 Gyr and [Fe/H]=−1.6, respectively (Suntzeff et al. 1986). About 20% of this “halo” is of the right abundance to make a Draco or UMi.

While the abundance arguments taken alone cannot rule out a scenario in which UMi and Dra are LMC or SMC tidal fragments, the age-metallicity relations for the Magellanic Clouds demand that this interaction happened “in the beginning.” First, it then seems more reasonable to argue that all of these galaxies were simply individual chunks of a protogalactic clump coming together to make the Milky Way. Second, since UMi is at the antipode of this LMC orbit, presumably the whole orbit would be populated. Since we argue here that UMi must split off at perigalacticon passage number 1, where are the results of the remaining many such passages? Why was the LMC or SMC fragile enough to be tidally disrupted on passage number one, but strong enough to have survived a Hubble time? Is such a scenario possible? The age-metallicity relations for the Magellanic Clouds, the properties of a “halo” field in the LMC, and the properties of the LMC RR Lyraes seem to be daunting foes of traditional tidal models.
Lin & Murray (1994) and Lin (1996) advocate models in which dSph's shared the Magellanic Cloud star-formation history until they were tidally removed. At tidal splitting the dSph's formed a second generation of stars. This model probably will not work to explain UMi and Draco, because of the age-metallicity relation and the star formation histories, and seems to fail in general.

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