Observed Properties of Dark Matter: dynamical studies of dSph galaxies

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The Milky Way satellite dwarf spheroidal (dSph) galaxies are the smallest dark matter dominated systems in the universe. We have underway dynamical studies of the dSph to quantify the shortest scale lengths on which Dark Matter is distributed, the range of Dark Matter central densities, and the density profile(s) of DM on small scales. Current results suggest some surprises: the central DM density profile is typically cored, not cusped, with scale sizes never less than a few hundred pc; the central densities are typically \(10^{-20}\) GeV/cc; no galaxy is found with a dark mass halo less massive than \(\sim 5 \times 10^7\) M\(_\odot\). We are discovering many more dSphs, which we are analysing to test the generality of these results.

I. INTRODUCTION AND METHODOLOGY

Determining the nature of the dark matter is one of the key goals of contemporary astronomy. The extremely large mass to light ratios for certain Local Group dwarf spheroidal (dSph) galaxies suggest that these are the most dark matter dominated stellar systems known in the Universe. Given the apparent absence of dark matter in globular clusters (length scale \(\sim 10\) pc), and the direct evidence that there is no dark matter associated with the galactic thin disk (length scale \(\sim 100\) pc; [8, 9]) the dSphs (characteristic radii \(\sim 300\)+ pc) are both the smallest systems to contain dynamically significant quantities of dark matter, and the most nearby systems where we may look for characteristic properties of the distribution of dark matter (maximum density, etc ...), which may provide some knowledge of its nature. Additionally, simulations of dark halo formation in a cosmological context predict that dSph galaxies are (unmodified?) survivors from the earliest structures formed, so that understanding their nature and structure also has general implications for galaxy formation and evolution.

Is it possible reliably to determine the dark matter distribution in a dSph galaxy? Fortunately, some dSphs are astrophysically simple, are old, are apparently in equilibrium, have no dynamically-significant gas, but contain a (small) number of stars, which provide ideal kinematic collisionless tracer particles. With the new generation of wide-field multi-object spectrographs on 4-8m telescopes, it is now viable to obtain sufficient high-quality kinematic data to determine the gravitational potentials in all the Galactic satellites. There are two types of analysis feasible with current datasets: a straightforward pressure-gravity balance analysis, based on the velocity dispersion moment, using the Jeans’ equations, and an analysis of the full projected kinematic distribution function, using the full information set but requiring more sophisticated analyses. These analyses are made more robust, and simplified, by stellar population studies of the dSph galaxies. Ultra-deep HST imaging for Draco [3] and UMi [17] show their stellar populations are indeed indistinguishable from those of old metal-poor globular star clusters, and hence have \(M/L_V \sim 2\).

The Jeans’ equations for a spherical stellar system lead directly to a model-independent mass estimator (see [111 Eq. 4-55 & 4-56]) requiring only knowledge of the velocity anisotropy and the true radial velocity dispersion \(\langle v_r^2\rangle\). Assuming spherical symmetry, it is straightforward to obtain \(\langle v_r^2\rangle\) from the line of sight velocity dispersion \(\langle v^2\rangle\) using Abel integrals. In applying the Jeans’ equation analyses, the spatially-binned dispersion profile is fit by an appropriate smooth function (figure 1), while the light is fit by a Plummer law, as this is an excellent fit to available star count data in all available cases (cf [4]).

FIG. 1: Draco surface brightness profile, with a fitted Plummer model, and the observed line of sight velocity dispersion profile, from [4].
The Jeans’ equation moment analysis involves two radial functions, the mass density and a possibly variable anisotropy in the stellar orbits, this second generating an anisotropic stress tensor. It is this anisotropic stress which gives the dSph galaxies their shapes, as direct observational limits exclude any angular momentum support against gravity. Equivalently, radially variable anisotropy is degenerate with mass (figure 2) making any deductions on the inner mass profile being cored or cusped in general model-dependent. Further information is needed to break this degeneracy, and fortunately is sometimes available, as we discuss below. In general however, full multi-component distribution-function models are required to use the information in the data to break this degeneracy.

II. RESULTS OF DYNAMICAL ANALYSES

Are dSph haloes cusped or cored? Debate continues to rage about whether the cusped haloes always created in CDM simulations are in conflict with observations of rotation curves of Low Surface Brightness galaxies. The gas-free nature of dSphs makes them kinematically clean systems in which to test theoretical predictions. Stellar velocities may also be used to place constraints on the steepness of any possible central cusp, whether due to a black hole, the intrinsic physical properties of the CDM (eg [14]), or possibly even CDM as modified by a central black hole (eg [12]).

As a general result, in all cases with sufficient data we rule out (King model) mass-follows-light models. King models are not an adequate description of these galaxies, all of which have high mass-to-light ratios (quoted in solar visual band units), and extended dark matter halos. Even in the inner regions mass does not follow light, while including outer data commonly we find a most likely global mass to light ratio which is very high, being for Draco $\sim 440$, 200 times greater than that for stars with a normal mass function (Fig. 1). The Draco halo models favoured by the data contain significant amounts of mass at large radii, leading to the observed flat to rising velocity dispersion profiles at intermediate to large radii.

In some cases (eg Draco, cf Figure 1) a decrease in the dispersion is apparent in the outermost data. This remains to be fully understood. The decrease is apparently steeper than Keplerian, so does not indicate the (first) detection of the outer limits of the galaxy. It cannot indicate tidal perturbations by the Milky Way galaxy, and in fact robustly excludes such complications, as tides heat and do not cool (eg [13]). It may indicate a combination of a radially-changing orbital anisotropy and a complex stellar kinematic distribution function (Figure 2). In any case, this illustrates that an adequate understanding of the very outer parts of the dSph is still lacking, so that we are unable as yet to determine outer mass distributions, or ‘total’ masses. The situation in the inner regions is however better defined and understood.

Figure 3 summarises Jeans equation models for several of the dSph, with in each case the simplest possible assumptions (isotropic radially-constant velocity distribution). It is apparent that the models are invalid at large radii, where an unphysical oscillation in the mass profiles is evident. In the inner regions however the fit to the data is good. In each case, a core-like mass distribution is preferred. As noted above however, it is possible, by adding a radially-variable stellar anisotropy (essentially an extra function) to the fit, to fit steeper cusp-like
central mass distributions.

Can one distinguish between shallow and steep density profiles using other information? Fortunately, in one special case, that of UMi, one can. In UMi, an otherwise very simple system from an astrophysical perspective, an extremely low velocity dispersion sub-structure exists (figure 4a). We explain this as a star cluster, which has become gravitationally unbound (the normal eventual fate of every star cluster, as mass is lost through normal stellar evolution), and which now survives as a memory in phase space. Why does it survive in configuration space? The group of stars have the same mean velocity as the systemic velocity of UMi, so they must orbit close to the plane of the sky, and hence through the central regions of UMi. As figure (4b) illustrates, this is possible only if the tidal forces from the UMi central mass gradient are weak. In fact, survival of this phase-space structure in configuration space requires that UMi has a cored mass profile. Similar results are provided by the survival of the globular cluster system in the Fornax dSph.

A. Distribution Function models

Standard cosmological simulations tend to overpredict the numbers of low-mass haloes surrounding Milky Way-type galaxies compared to observations. One possible solution (eg.11) is that all dwarf galaxies have very extended haloes, and are therefore very much more massive than previously thought. According to the Stoehr et al. analysis, the observed dispersion profile of Draco and Fornax can be obtained by embedding the stellar distributions in ΛCDM haloes of masses \( \gtrsim 10^9 M_\odot \), extending to several kpc. While our existing data on Draco are compatible with this hypothesis, it is not known whether it holds in general. More reliable masses and mass profiles are therefore desirable.

The principal objective of our dynamical modelling work to date has been to move beyond the traditional King models for dSphs, in order to break the principal degeneracy of the problem, namely that a large velocity dispersion at large radii in a dSph can be explained either by the presence of large amounts of unseen mass at large radii, or by tangential anisotropy of the velocity distribution. We have therefore developed a family of dynamical models (described in detail in 15) which span the full range of possible halo models from mass-follows-light to extended haloes. The models also incorporate anisotropy in the velocity distribution. Our current modelling has focused on spherically symmetric dark haloes and stellar distributions. Our analysis of our Draco data, together with extensive Monte Carlo simulations, has demonstrated that data sets of several hundred radial velocities are sufficient to discriminate between halo models and to break the degeneracy between mass and velocity anisotropy, provided these data are at sufficiently large radii \( 4, 15 \). The outermost data also place constraints on any systemic rotation or tumbling which might contribute, along with anisotropic kinematics, to the flattening seen in some dSph galaxies, and provide further direct tests that a system is unaffected by tides, so that an equilibrium dynamical analysis is appropriate.

The results of spherical modelling supports the basic results of the Jeans’ equation analysis, though of course use more information, so are more robust. We are currently implementing new families of models to allow more robust distinction between cored and cusped mass distributions in the dSph. One new option allowed by extant...
DF models is to test the viability of the alternative gravity theory, MOND. Wilkinson et al. have carried out such an analysis, concluding that even with MOND dark matter is required. Available data for the Fornax dSph can in fact be modelled quite well by MOND, assuming the MOND scale parameter to be $a_0 = 2.1 \times 10^{-8}$ cms$^{-2}$. For UMi and Draco, however, even MOND requires either a high M/L value ($\sim 20$), or a very different length scale parameter ($a_0 \sim 50 \times 10^{-8}$ cms$^{-2}$).

Secondly, all the dSph we have analysed to date show very similar, and perhaps surprisingly low, central dark matter mass densities, with a maximum value of $\sim 5 \times 10^8 M_{\odot} kpc^{-3}$, equivalent to $\sim 20$ GeV/cc. Interestingly, the rank ordering of the central densities is in inverse proportion to system total luminosity, with the least luminous galaxies being the most dense. This is of the opposite sign to some CDM predictions, though we note a yet further complication involving system mass below, since most CDM simulations predict mass rather than luminosity.

We have not yet detected a reliable Keplerian decline, or any evidence for tidal truncation, in any dSph galaxy dark halo studied so far. We therefore (still) have no total mass determinations. Nonetheless, the total masses determined out to the limits of the stellar distribution show an interesting systematic effect. This is shown in Figure 5, a plot whose style is adopted from [10]. Figure 5 displays the relationship between the luminosity of the lowest-luminosity Local Group galaxies against the derived (logarithmic) system mass-to-light ratio. In this parameter space, the solid curve shows the relationship anticipated if every dSph galaxy contains the same mass of dark matter - in this case some $\sim 4 - 5.10^7 M_\odot$ within the volume which contains its stellar population. The system total luminosity is measured directly.

It is apparent from Figure 5 that there is remarkably little spread in mass apparent among the galaxies with absolute magnitude fainter than $\sim -11$. This relation was considered until recently to be a minor curiosity, since it covered the dynamic range only from $M_V \sim -13$ to $-9$, a mere factor of forty or so in luminosity, and included only 8 galaxies. However, the recent analysis [10] of the newly-discovered extremely low luminosity dSph galaxy UMa has extended the validity of the relation by another two magnitudes, now a factor of $\sim 200$ in luminosity, and to total mass-to-light ratios in excess of 1000. Several other new very low luminosity dSph satellite galaxy candidates have been discovered in the last few months, while new studies of several known galaxies have recently been completed [2]. It will be very interesting to see if these dynamical studies strengthen or disprove this apparent trend.

**III. GENERAL RESULTS: SYSTEMATIC PROPERTIES OF DARK MATTER ON SMALL SCALES**

![Figure 5: Mass to light ratios vs galaxy absolute V magnitude for some Local Group dSph galaxies. The solid curve shows the relation expected if all the dSph galaxies contain about $4 \times 10^7$ solar masses of dark matter interior to their stellar distributions.](image)

The profiles in figure 3, derived by Jeans’ equation analyses, illustrate two of our basic results. In every case, the simplest analysis favours cored mass distributions. While cusped mass distribution can usually be fit to the data, in at least one case, UMi, there is very strong direct evidence that a cusp model is inadequate to explain all the available information. The conservative assumption is therefore that all the mass profiles are indeed cored, and are significantly shallower than $r^{-1}$.

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