DARK MATTER IN THE LOCAL GROUP

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ABSTRACT

The contribution of Gaia to our understanding of dark matter in the local Universe is summarised. Particular highlights will include accurate determinations of the masses and extents of the Milky Way and Andromeda dark matter haloes, full space motions of satellite galaxies making it possible to identify dark matter associated with a Local Group halo, and constraints on the nature of the dark matter from observations of wide binaries.

Key words: Stellar dynamics; Galaxy: kinematics and dynamics; Dark matter.

1. INTRODUCTION

Dark matter is generally believed to provide the gravitational potential wells in which galaxy formation takes place. Determining the nature of the dark matter is therefore a prerequisite for a complete understanding of galaxy formation and evolution. The existence of dark matter in the universe was first proposed by Zwicky (1937) to explain his observation that the measured velocities of galaxies in the Coma cluster were much too large for the cluster to remain bound if the only gravitational potential was provided by the observed galaxies in the cluster. In the subsequent decades, the range of systems which appear to contain dark matter has grown substantially. On the largest scales, there is impressive agreement between cosmological simulations of structure formation in a ΛCDM universe (the currently favoured cosmological model with a non-zero cosmological constant Λ and cold dark matter) and observations of the large scale distribution of galaxies (Ostriker & Steinhardt 2003). On the scale of galaxy clusters, gravitational lensing and X-ray studies have demonstrated the presence of dark matter in these systems (e.g., Bartelmann 2003; Buote 2004) while on galactic scales, the presence of dark matter haloes surrounding the visible galaxies is deduced from observations of the flatness of disc galaxy rotation curves (e.g., Sofue & Rubin 2001).

However, despite more than half a century of observational and theoretical effort, answers to the three key questions about dark matter remain conspicuously elusive:

- How is the dark matter distributed?
- What is the dark matter?
- Does dark matter exist?

The aim of this article is to illustrate the contributions which the Gaia data set is expected to make towards providing answers to these questions.

2. HOW IS THE DARK MATTER DISTRIBUTED?

The mass distribution within the dark haloes of galaxies provides clues to the nature of the dark matter they contain. For example, numerical simulations have shown that the number of satellite haloes orbiting within the halo of a Milky Way type galaxy is larger if the dark matter is cold (i.e., is composed of non-relativistic particles) than if the dark matter is warm (i.e., has a non-zero velocity dispersion at early times). In addition, the mean densities of dark haloes are lower, and their inner density profiles are less steep, in the warm dark matter scenario (e.g Bode et al. 2001). The presence of a significantly flattened dark component in the Milky Way would also have implications for the nature of the dark matter, since a disc component would not be expected if dark matter is dissipationless, as is generally assumed. The principal contribution of Gaia to the study of dark matter will be in mapping out the dark matter distribution of the Milky Way as well as that of the Local Group. In order to determine the distribution of dark matter in any stellar system, we need large kinematic data sets of tracer objects whose motions trace out the underlying mass distribution. The large data set of tracers provided by Gaia will be unique both in terms of size and completeness and therefore the majority of this article is devoted to this aspect of dark matter studies.

2.1. Disc Dark Matter

The presence of a flattened component in the dark matter distribution of the Milky Way would imply that at least some of the dark matter is dissipational, for example in the form of cold gas (e.g., Combes & Pfenniger

1997). Locally, we can test for the existence of any putative disc dark matter by comparing estimates of the local mass density based on stellar kinematics with those based on the amount of visible mass in the form of stars and gas. A number of authors have investigated this problem. Based on the radial velocities of a sample of disc K dwarfs, Kuijken & Gilmore (1991) showed that the local surface mass density of the disc is $\Sigma_{\rm d}(R_0) = 48{\pm}9$ $\mathrm{M}_\odot$ pc^{-2}. Crézé et al. (1998) used a sample of tracers with distances and proper motions taken from the Hipparcos data set to determine the local volume mass density: they found that $\rho_0 = 0.076{\pm}0.015$ $\mathrm{M}_\odot$ pc^{-3}. The estimates of both $\Sigma_{\rm d}(R_0)$ and ρ_0 are broadly consistent with the observed mass in stars and gas. If we assume that the dark halo of the Milky Way is spherical, then a contribution of about 0.008 $\mathrm{M}_\odot$ pc^{-3} to the local mass density would be expected. Crézé et al. (1998) conclude that there is just room for this contribution within the measured mass estimates, but no unseen flattened component can be accommodated.

Gaia will contribute to our understanding of the mass distribution within the disc in two main ways. First, Gaia will improve our knowledge of the low-mass end of the stellar mass function both directly in terms of raw numbers of observed low-mass stars and indirectly via the determination of the binary fraction and mass-luminosity relation for low-mass stars. This information will reduce the uncertainties in estimates of the directly observable contributions to the local mass budget.

Second, and probably more significantly, Gaia will improve our knowledge of the stellar kinematics within the disc of the Milky Way, thereby improving the precision of kinematic mass estimates of the disc. The uncertainty in present estimates stems from our lack of knowledge of the stellar velocity distribution function as a function of position within the disc. The Jeans equations in cylindrical coordinates may be used to relate the z-component of the gravitational force $F_{\rm z}$ (where the z direction is perpendicular to the plane of the disc) due to a flattened mass distribution to the number density $\nu(r)$ and velocity distribution of a tracer population via (e.g., Kuijken & Gilmore 1989)

$$\nu F_{\rm z} = \frac{\partial(\nu\overline{v_{\rm z}^2})}{\partial z} + \frac{1}{R}\frac{\partial(R\nu\overline{v_{\rm R}v_{\rm z}})}{\partial R} \qquad (1)$$

Here $\overline{v_{\rm z}^2}$ is the vertical velocity dispersion and $\overline{v_{\rm R}v_{\rm z}}$ represents the coupling between the vertical ($v_{\rm z}$) and radial ($v_{\rm R}$) motions. Currently, the second term on the right hand side of Equation 1 is only weakly constrained by observations (Bienaymé 1999). Its value depends on the tilt of the stellar velocity ellipsoid, i.e., on whether the stellar velocity distribution is aligned with the axes of a cylindrical or spherical coordinate system (see Figure 1). Gaia will accurately determine the velocity distribution within 1 kpc of the Sun. This will immediately make it possible to improve the accuracy of local disc mass estimates.

Gaia will also determine which stellar populations can be reliably used as kinematic tracers. There is growing evidence that the velocity distribution in the solar neighbourhood is not smooth, but instead contains significant

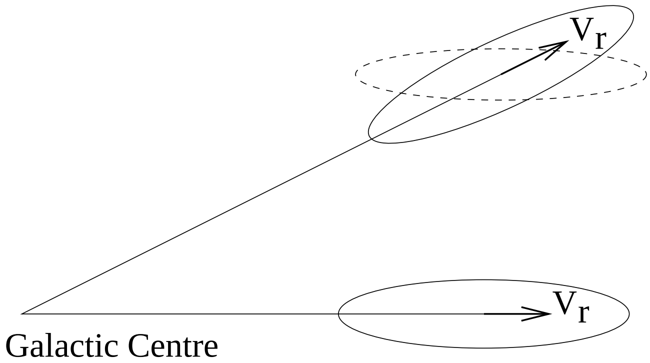

Figure 1. Schematic diagram of the possible change in the orientation of the stellar velocity distribution with height in the Galactic disc. The lower ellipse represents the velocity distribution close to the Sun. The upper ellipses show two possible orientations of the velocity distribution out of the Galactic Plane. The solid ellipse corresponds to the case in which the velocity distribution is aligned with the axes of a spherical coordinate system while the dotted ellipse is for a distribution aligned with a cylindrical system.

amounts of substructure (see e.g., Dehnen 2000; Famaey et al. 2004). The selection of tracers which appear to be close to a steady-state (e.g., populations without a net outward/inward velocity) is essential for a determination of the disc mass distribution. In addition, Gaia will determine the velocity distribution over a significant fraction of the Galactic disc. This information can be used to obtain a mass estimate of the entire disc which in turn will constrain the amount of dark matter required to produce the flat circular velocity profile of the Milky Way.

2.2. The Local Escape Speed

Another constraint on the dark matter halo of the Milky Way comes from the escape speed from the solar neighbourhood $v_{\rm e}$. Stars with velocities above the escape speed have sufficient kinetic energy to escape from the Galactic gravitational potential: the escape speed thus constrains the depth of the halo potential well. (It is important to note that the extent of the dark halo is not constrained by the escape speed alone – this requires additional information about the shape of the mass distribution). When estimating $v_{\rm e}$, a key uncertainty is the shape of the velocity distribution of high velocity stars. For stars whose space velocities v lie close to $v_{\rm e}$, Leonard & Tremaine (1990) assume a velocity distribution of the form

$$f(v|v_{\rm e},k) \begin{cases} \propto (v_{\rm e}-v)^k, & v < v_e \\ = 0, & v \geq v_e \end{cases} \qquad (2)$$

which is essentially the first term in a Taylor expansion of the full distribution function near $v_{\rm e}$. The index k depends on the (unknown) details of the velocity distribution – plausible values lie in the range 1–2. Leonard & Tremaine (1990) used a Bayesian analysis to determine the value of $v_{\rm e}$ which best reproduced the Carney & Latham (1987) data set of high velocity stars. They concluded that v_e lies in the range 450 – 650 km s^{-1} with 90% confidence. More recently, Meillon et al. (1998) analysed a combination of high velocity stars obtained from the Hipparcos data set and the earlier Carney et al. (1994) sample and found that v_e cannot exceed 530 km s^{-1}. This analysis assumed the same velocity distribution as that given above.

As Leonard & Tremaine (1990) emphasise, estimates of v_e are very sensitive to the velocity of the highest velocity star in the sample (the highest space velocity in the Meillon et al. (1998) sample was 458 km s^{-1}). Gaia will improve the situation in a number of ways. First, by dramatically increasing the sample of high velocity stars with measured space motions Gaia will constrain the shape of the high velocity tail of the stellar velocity distribution – the Meillon et al. (1998) sample contains only four stars with velocities above 400 km s^{-1}. This will determine the required value of k observationally, and also enable us to test whether the form given in Equation 2 is actually appropriate. Second, the velocity errors on the highest velocity stars in present samples are large (up to 60 km s^{-1}) which also impacts on the precision of the estimated v_e. Gaia will obtain significantly more accurate velocities for high velocity stars in the solar neighbourhood.

Figure 2 (reproduced from Sakamoto et al. 2003) provides a graphical illustration of the difficulty of estimating the Galactic escape velocity at larger radii using current data sets – the situation mirrors the problem in the vicinity of the Sun. For a variety of halo tracers including satellite galaxies (squares), globular clusters (circles) and field horizontal branch stars (FHB: triangles), the Figure plots the Galactic rest frame velocities ($V_{\rm RF}$) versus the escape velocity ($V_{\rm esc}$) at the present location of the tracer assuming a Galactic potential $\psi(r)$ of the form

$$\psi(r) = \frac{GM}{a} \log \left(\frac{\sqrt{r^2 + a^2} + a}{r} \right) \qquad (3)$$

Here the scale length a = 195 kpc and the total mass M are chosen to give a circular speed of 220 km s^{-1} at the position of the Sun. The two velocities are equal on the diagonal line – objects below the line are bound by the model Galactic potential while those above are not. The Figure clearly shows that the number of objects which lie close to the escape velocity is very small, and additionally that the errors on the velocities of these objects are very large, compounding the problem of estimating v_e reliably. The FHB stars in this Figure extend to distances of 10 kpc. Ideally, one would like to use such a data set to determine the escape velocity as a function of radius – this is clearly impossible using the currently available data. Gaia will provide accurate space motions for FHB stars to distances of around 15 kpc (assuming that their distances can be estimated from their absolute magnitudes). These data will be sufficiently numerous ($\sim 10^4$ objects) to allow a radial profile of the escape velocity to be determined – this will place the first direct constraints on the profile of the dark matter halo at the radius where its mass begins to dominate the Galactic potential.

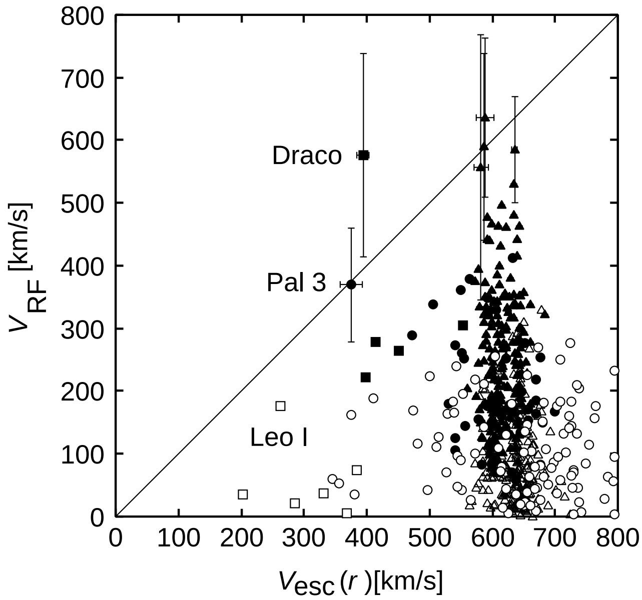

Figure 2. Galactic rest frame velocities ($V_{\rm RF}$) versus local escape velocity ($V_{\rm esc}$), assuming a halo of the form given in Equation 3 for a range of halo tracers: satellite galaxies (squares), globular clusters (circles) and field horizontal branch stars (triangles). Filled or open symbols denote objects with or without measured proper motions, respectively. Reproduced, with permission, from Sakamoto et al. (2003).

2.3. The Extent of the Milky Way Halo

As was discussed above, measuring the local Galactic escape velocity alone does not constrain the extent of the dark halo. To determine the overall mass and extent of the halo, a sample of tracers at large radii is required. At present, the number of tracer objects at sufficiently large radii is very small: there are about 30 satellite galaxies and globular clusters which lie in the radius range 20–350 kpc and this number is unlikely to increase. Proper motion estimates are available for a number of these objects, but are very uncertain. As a result, the true uncertainties in estimates of the halo mass at large radii are at least a factor of two (see Figure 3 Wilkinson & Evans 1999). Although the Gaia proper motions for individual stars in the satellite galaxies and globular clusters will not be particularly accurate (and radial velocity measurements will be possible only for a handful of the brightest stars in each system) all the Milky Way satellites, including the distant LeoI dwarf spheroidal galaxy, contain sufficient numbers of stars brighter than the Gaia magnitude cut-off to ensure that estimates of the ensemble tangential velocity with errors of 10–20 km s^{-1} will be feasible. As Figure 3 shows, precise knowledge of the space motions of 30 (independent) tracers probing the entire halo removes the systematic uncertainties from mass estimates, as well as reducing the random errors.

Given that the number of satellite galaxies and globular clusters is unlikely to change, stellar tracers of the halo constitute the most promising way to increase the size

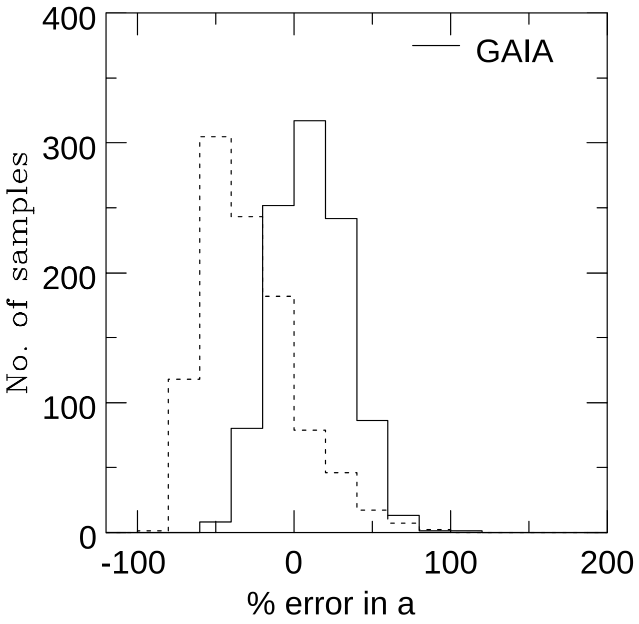

Figure 3. Histograms illustrating the impact of Gaia on the determination of the scale length a of the Milky Way halo, assuming a halo potential of the form given in Equation 3. The histograms show how many out of 1000 data sets yielded a given percentage error in a. The dashed histogram illustrates (approximately) the present situation: 30 points with radial velocities only. There is evidence for a systematic underestimate in the value of a obtained as well as a significant scatter about the mean estimated value. The solid histogram is for 30 tracers with both radial velocities and proper motions. The latter case is how the data set will look after the Gaia mission: the systematic underestimate has been removed and the scatter about the mean is reduced to about 20%. Reproduced from Wilkinson & Evans (1999).

of available data sets of halo tracers. Already, various ground-based surveys are acquiring data sets of blue horizontal branch stars at large radii (e.g., Sirko et al. 2004; Clewley et al. 2004; Brown et al. 2003). The difficulties of carrying out ground-based, spectroscopic surveys over large areas of sky are obvious. At the distances (and magnitudes) of interest ($\geq$ 10 kpc), Gaia parallax measurements will be too uncertain to be useful – most distance estimates will therefore rely on knowledge of the absolute magnitudes of the tracers. These will be much more accurately determined by Gaia, along with any dependence of absolute magnitude on metallicity or other internal parameters. The presence of the Radial Velocity Spectrograph (RVS) on board Gaia will provide the third velocity component needed for accurate kinematic modelling. Based on the current estimates of the performance and limiting magnitude of the RVS (Katz et al. 2004), Gaia will obtain usable radial velocities for

- About 10^4 Blue Horizontal Branch stars ($M_v \sim 0.6$) to radii of about 15 kpc;
- Several hundred Red Giant Branch tip stars ($M_v \sim -2.0$) to radii of 50 kpc;

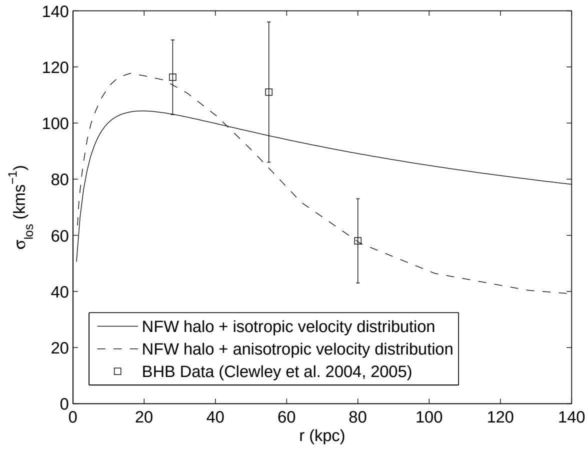

Figure 4. Line of sight velocity dispersion profile for a sample of halo Blue Horizontal Branch stars from the sample of Clewley et al. (2004, 2005). The outermost bin has a significantly smaller velocity dispersion than that observed inside 60 kpc. The majority of the stars in this bin may be associated with the Magellanic Stream. Overplotted are two model fits to the observed dispersion profile – see the text for a detailed discussion.

- Asymptotic Giant Branch stars ($M_v \sim -2.5$) out to 60 kpc;
- About 10^3 CH carbon stars ($M_v \sim -2.5$) out to 60 kpc.

If we (conservatively) assume that tracer distances can be obtained with 10 per cent accuracy and that the typical tangential velocity of a halo star is about 100 km s^{-1}, then transverse velocities of comparable accuracy to the radial velocities (10–15 km s^{-1}) can be obtained for all the above tracers to similar galactocentric distances. Thus, we can expect to have full space motions for samples of several thousand stellar tracers out to 50–60 kpc. Reductions in the distance errors will permit transverse velocities to be obtained to somewhat larger distances. For example, if the distance errors are 5 per cent then the radial limit for CH carbon stars increases to 70 kpc – for tracers beyond 60 kpc accurate radial velocities will have to be obtained from ground-based follow-up.

Wilkinson & Evans (1999) used Monte Carlo simulations to demonstrate that a sample of 500 stellar tracers (with radial velocities only available) probing to radii of 50 kpc is sufficient to reduce the uncertainties in the enclosed halo mass to about 10 per cent. The availability of proper motions will further reduce the uncertainty and will also directly constrain the anisotropy of the velocity distribution. Thus, in the post-Gaia era we can expect to be able to determine the mass of the Milky Way halo within 50–60 kpc to significantly better than 10 per cent accuracy.

As an illustration of the importance of large kinematic data sets in the study of the Galactic halo, Figure 4 shows the variation of the line of sight velocity dispersion with galactocentric radius for a sample of halo Blue Horizontal Branch (BHB) stars obtained by Clewley et al. (2004, 2005) using both the William Herschel Telescope, La Palma, and ESO's Very Large Telescope (VLT). The outermost bin corresponds to a sample of eight BHB stars from the VLT which span the radius range 65 – 101 kpc and display a velocity dispersion which is significantly smaller than that of the inner sample. The overplotted curves are the expected dispersion profiles for a pressure-supported tracer population with a power law density distribution (the BHB density is assumed to fall off as $r^{-3.5}$) embedded in a dark matter halo whose density $\rho(r)$ has the form (Navarro et al. 1996):

$$\rho(r) = \frac{\rho_s r_s^3}{r(r + r_s)^2} \quad (4)$$

The solid curve shows the best fitting profile when the tracer population is assumed to have an isotropic velocity distribution. The dashed curve shows the dispersion profile for a model constructed following the prescription of Gerhard (1991) for the generation of distribution functions in which the velocity distribution becomes increasingly tangentially biased at large radii. This model clearly matches the data at large radii much more closely than the isotropic model. However, it should be noted that the parameters required to produce this fit are not very plausible, as they imply that the velocity distribution changes from isotropic to almost purely tangential over a very small range of galactocentric radii.

Further analysis of the outer BHB data reveals that their positions and velocities are consistent with their being associated with the Magellanic Stream (see Clewley et al. 2005, for a detailed discussion of this analysis). If a majority of the outer BHB stars in our sample are members of a kinematically distinct sub-population then the dispersion profile shown in Figure 4 is not very meaningful. The all-sky nature of the Gaia data set will make it possible to distinguish between general properties and localised features of the stellar halo. Figure 4 also emphasises the advantage of simultaneously obtaining the radial velocities and proper motions for tracers. In the absence of proper motions, the lack of constraints on the models makes it difficult to rule out extreme models such as the anisotropic model shown in the Figure. Full space velocities for large samples of tracers will immediately allow us to look for unexpected changes in the velocity distribution as a function of radius. In addition, the identification of stellar streams in the halo provides a useful avenue to test for signatures of non-sphericity in the gravitational potential of the halo (e.g., Helmi 2004; Ibata et al. 2001; Martínez-Delgado et al. 2004). The cold stellar streams produced by the disruption of satellite galaxies remain spatially confined in spherical haloes while the precession of orbital planes in triaxial haloes leads to the spreading out of streams in configuration space – although they can still be identified using their integrals of motion (see e.g., Helmi et al. 1999). The properties of the streams identified by Gaia will constrain the non-sphericity of the Milky Way halo.

2.4. The M31 Halo and Local Group Dark Matter

The Andromeda galaxy (M31) is the other massive spiral galaxy in the Local Group and, as such, is a useful object for comparison with the Milky Way (see Hodge 1992, for a detailed review). Although conventional wisdom has always asserted that Andromeda is the more massive galaxy, recent estimates of the mass of its dark halo based on the kinematics of its satellite galaxies and globular clusters have found that there is no dynamical evidence to back up this claim (Evans et al. 2000; Evans & Wilkinson 2000; Côté et al. 2000; Gottesman et al. 2002). Currently, the data set consists of the three-dimensional positions and radial velocities of the satellite galaxies and the projected positions and radial velocities of the globular clusters. Gaia will provide space motions for the satellite galaxies of M31 and for some of the brighter globular clusters (the accuracy of the radial velocities for globular clusters based on their integrated RVS spectra has yet to be established, but we note that velocity errors of about 10 – 15 km s^{-1} would be acceptable for constraining the halo mass of M31). As in the case of the Milky Way, the improvement in mass estimates based on full space motions will be considerable. In addition, the RVS will provide radial velocities for some bright stellar tracers (for example AGB stars) in the halo of M31. These combined improvements in the kinematic data will reduce the uncertainties on the mass within about 50 kpc to below 10 per cent.

The relative orbit of the Milky Way and M31 also places important constraints on the distribution of dark matter in the Local Group. Kahn & Woltjer (1959) showed that the total mass of the Local Group can be estimated by making plausible assumptions about the shape of the Milky Way/M31 orbit. More recent estimates based on satellite motions (e.g., Schmoldt & Saha 1998; Peebles 1996) have found that the total mass of the Local Group is approximately $4 - 8 \times 10^{12}$ M$_{\odot}$. Given that the estimates of the Milky Way and M31 haloes suggest that their individual masses are around $1 - 2 \times 10^{12}$ M$_{\odot}$, it would appear that at least 50 per cent (and perhaps almost all) of the mass in the Local Group is associated with its most massive component galaxies. On the other hand, Sembach et al. (2003) have found some evidence for the existence of hot ($> 10^6$K) gas associated with the Local Group (as opposed to either the Milky Way or M31). The existence of Local Group dark matter is clearly important for the evolution of the group. The recent simulations of Sawa & Fujimoto (2005) have emphasised the significance for the satellite distribution of possible past interactions between the Milky Way and Andromeda – such interactions will be strongly affected by the presence of an external potential.

Gaia will provide a robust measurement of the space velocity of M31, an essential ingredient in any orbital analysis of the Local Group but which is currently unknown. The preferred model for the history of the Local Group presented by Sawa & Fujimoto (2005) predicts M31 proper motions of (μ_l, μ_b) =(38, -49) μas yr^{-1}. Given that M31 contains a few$\times$ 10^5 stars brighter than V = 20, an accuracy of 10 – 20 km s^{-1} on the transverse velocity will be obtained easily from the Gaia data set. In addition, as discussed above, Gaia will provide the space motions for about twenty of the satellite galaxies of the Local Group. These can be used to build consistent models of the origin and evolution of the Group. In particular, the effect of a significant Local Group gravitational potential, not associated with either the Milky Way or M31 haloes, will be detectable.

2.5. Dark Matter in Dwarf Spheroidal Galaxies

Up to this point, we have been considering the dark matter distribution in the haloes of the massive Local Group galaxies, as it is on our understanding of these systems that Gaia will have the greatest impact. However, the dwarf spheroidal galaxies (dSphs) orbiting the Milky Way themselves present a particular opportunity to constrain dark matter models. The extremely large estimated mass to light (M/L) ratios for the Draco (Kleyna et al. 2001) and Ursa Minor (UMi) dSphs suggest that they are extremely dark matter dominated systems which may also represent a fundamental length scale as the smallest systems to contain dynamically significant quantities of dark matter – globular clusters, the next step down in physical scale from the dSphs do not appear to contain dark matter. These systems are potentially very useful – if the haloes of dSphs are pristine and undisturbed then their properties (e.g., length-scale, mean density, etc) place tight constraints on the properties of the dark matter they contain. It is therefore essential to understand both the origin of the observed dSphs and the extent to which their intrinsic properties have been modified due to the proximity of the Milky Way.

Due to the distance of the majority of Milky Way dSphs, Gaia will yield only very limited information on the internal kinematics of these objects – low resolution transverse velocity maps may be possible by binning the proper motion data. Nevertheless, Gaia will provide useful data for the study of the dark haloes of dSphs. Figure 5 shows the projected line of sight velocity dispersions of the Draco and Ursa Minor dSphs as a function of projected radius. Both profiles are flat out to large radii – detailed modelling has shown that this is indicative of the presence of significant quantities of dark matter (Kleyna et al. 2001). Unexpectedly, the velocity dispersion in the outer bin of each galaxy drops significantly. The origin of this population is not yet clear, but it may be due to the action of the Milky Way tidal field (Wilkinson et al. 2004). Figure 6 shows the surface density profile of the Draco dSph. At the Figure shows, there is a change in the slope of the light distribution at approximately the same radius as the change in the velocity dispersion – a similar feature is seen in the profile of Ursa Minor (Palma et al. 2003; Martínez-Delgado et al. 2001).

Determining whether the features seen in the Draco and Ursa Minor dSphs are genuine tidal tails and how far they actually extend are very important questions which are extremely time-consuming to answer from ground-based surveys but which have the potential to provide much information about the dark matter content of dSphs. For example, if dSphs currently possess massive, extended haloes then one would not expect to see significant tidal

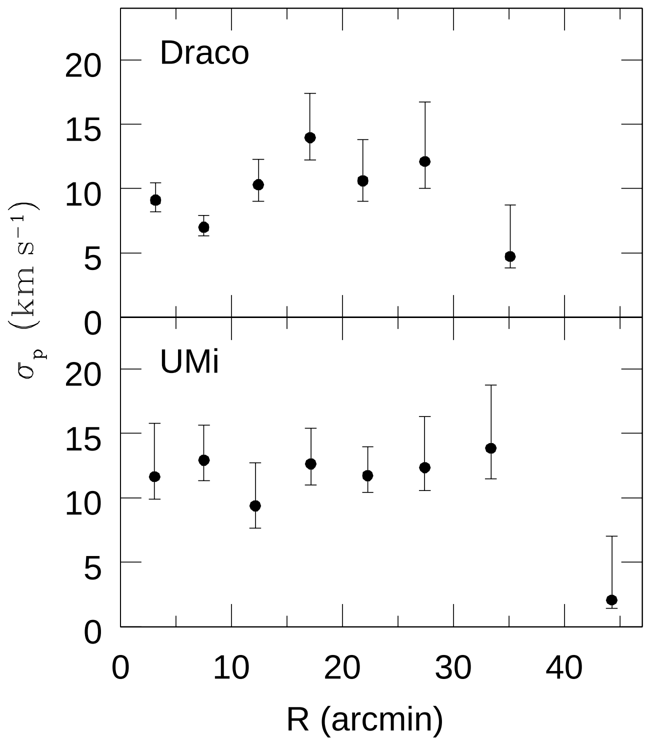

Figure 5. Projected velocity dispersion profiles for the Draco (top) and Ursa Minor (bottom) dwarf spheroidal galaxies. Figure reproduced from Wilkinson et al. (2004).

features. Gaia will facilitiate the kinematic identification of extended tidal features associated with dSphs. Along favourable lines of sight, Gaia will be able to distinguish between tail stars and foreground stars simply by virtue of their different proper motion signatures (e.g., King et al. 1998). For the majority of dSphs, however, a combination of broadband photometry and proper motion information will be required to produce a clean sample of tail stars. These stars can subsequently be followed up spectroscopically from the ground to obtain radial velocities and confirm their association with the dSph.

3. WHAT IS THE DARK MATTER?

As we have seen, Gaia will facilitate the construction of a detailed map of the dark matter distribution in the Local Group which will contribute to our understanding of the nature of the dark matter. However, Gaia will also provide a direct test for the presence of compact dark objects in the Galactic halo by greatly increasing the sample of wide stellar binaries.

In their comprehensive study of wide stellar binaries, Chanamé & Gould (2004) identified a sample of 116 wide binaries in the stellar halo using the revised New Luyten Two-Tenths Catalog (Gould & Salim 2003; Salim & Gould 2002). These binaries have separations of up to 1 pc. Chanamé & Gould (2004) find that the distribution of separations is well described by a single power law for binary separations between 3.8×10^{-3} pc and 1 pc. Yoo

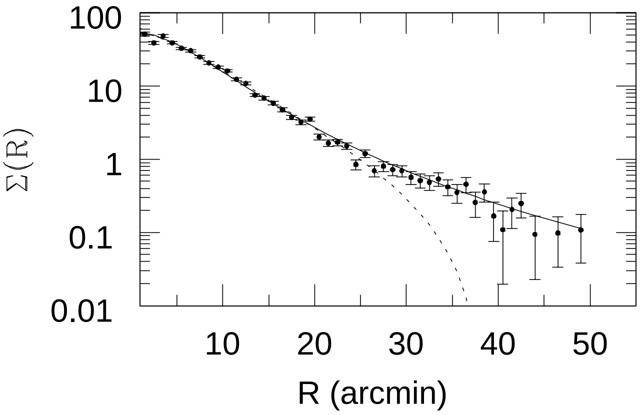

Figure 6. Surface brightness profile of the Draco dwarf spheroidal galaxy, based on deep imaging to V ≈ 25 and i′ ≈ 24 with the Isaac Newton Telescope. The data have been corrected for the effects of variable extinction using the reddening map of Schlegel et al. (1998). Figure reproduced from Wilkinson et al. (2004).

et al. (2004) subsequently demonstrated that the form of the separation distribution constrains the possible masses of compact objects in the Galactic halo. They showed that encounters between wide binaries and massive compact objects would result in the power-law tail of binary separations becoming steeper with time and argued that the absence of a cut-off (or change in power law index) in the distribution of wide binary separations rules out a significant fraction of the local halo density being in the form of compact objects with masses above $43\ \mathrm{M}_\odot$. Given the implications of these results for our understanding of the dark matter, it is important to extend the sample to include more binaries (the sample used by Yoo et al. (2004) contains only two binaries at the widest separation), and to cover a larger volume of the Galactic halo (the median distance of the binaries in the Yoo et al. (2004) sample is 240 pc). The availability of RVS radial velocities will confirm the common space motion of the binaries, reducing the risk of contamination from physically unrelated pairs possessing similar proper motions. In addition, the detailed information provided by Gaia about the properties of the individual components will constrain models of the formation of these binaries. Most importantly, knowledge of the Galactic orbits of these binaries will enable us to investigate how and where they formed and hence to determine how long they have been exposed to potentially disrupting encounters with halo substructure at the local halo density. This information will make it possible to put stronger constraints on the contribution of massive compact objects to the mass budget of the Milky Way.

4. DOES DARK MATTER EXIST?

Although this contribution has focused on the role of Gaia in pinning down the properties of the dark matter, a discussion of dark matter would be incomplete without some consideration of the alternative. The difficulty of reconciling the results of cosmological simulations with observations on sub-galactic scales (i.e., length scales of a few kpc or less) and the on-going failure to identify the dark matter has fuelled interest in alternative explanations for the observational data from which the presence of dark matter is traditionally inferred. In the Milky Way, the divergence between the dark matter predictions and observations is becoming increasingly acute as dynamical modelling appears to leave no room for significant quantities of dark matter inside the solar circle (Bissantz et al. 2003; Binney & Evans 2001).

The MOdified Newtonian Dynamics (MOND) of Milgrom (1983) has enjoyed some success in recent years in explaining the flat rotation curves of spiral galaxies without the need for dark matter (Sanders & McGaugh 2002). In MOND, Newton's Law of gravity is modified for accelerations smaller than a universal scale $a_0 \sim 1 \times 10^{-8}\ \mathrm{cm\,s^{-2}}$. This idea has recently received a significant boost following the publication of a relativistic theory which incorporates MOND as a non-relativistic limit (Bekenstein 2004). In addition to being Lorentz covariant, this new formulation also yields the correct value for the deflection angle due to gravitational lensing. It is likely that, over the coming years, considerable effort will be expended in testing MOND more fully.

The outer regions of globular clusters are promising places to compare MOND with Newtonian gravity as in certain clusters the internal accelerations fall below a_0 in the outer parts (e.g., Baumgardt et. al 2005). In such clusters, one would expect the internal dynamical evolution of a MOND cluster to differ from that expected in standard Newtonian theory (Ciotti & Binney 2004). Gaia data in the outer regions of globular clusters may therefore be able to contribute to the comparative assessment of dark matter and non-dark matter models. Further numerical work is needed to quantify more fully the differences between MOND and standard star clusters and to determine the precise contribution of Gaia in this area.

5. CONCLUSIONS

The richness of the Gaia data set hardly needs reiterating in a proceedings devoted to the scientific harvest of the mission and so I will end by simply emphasising those features of the Gaia data which make it particularly suitable for the study of dark matter. Uniquely among upcoming Galactic surveys, Gaia will observe the entire sky to sufficiently faint magnitudes to provide significant numbers of distant halo tracers with which to constrain the mass, extent and shape of the Milky Way halo. The space motions of Andromeda, and of the satellite galaxies of the Local Group, will be obtained precisely for the first time, placing limits both on the mass of the individual haloes of the Milky Way and M31 and on the presence of dark matter associated with the Local Group. In addition, Gaia will provide an opportunity to constrain some of the detailed properties of the dark matter through the identification of wide stellar binaries in the Galactic halo. The detailed map of Local Group dark matter obtained by Gaia will provide us with many new insights into the nature of this important component of the Universe.

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