Rotation of halo populations in the Milky Way and M31

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ABSTRACT

We search for signs of rotation in the subsystems of the Milky Way and M31 that are defined by their satellite galaxies, their globular cluster populations and their Blue Horizontal Branch (BHB) stars. A set of simple distribution functions is introduced to describe anisotropic and rotating stellar populations embedded in dark haloes of approximate Navarro–Frenk–White form. The BHB stars in the Milky Way halo exhibit a dichotomy between a prograde-rotating, comparatively metal-rich component ([Fe/H] > −2) and a retrograde-rotating, comparatively metal-poor ([Fe/H] < −2) component. The prograde metal-rich population may be associated with the accretion of a massive satellite (~10^9 M⊙). The metal-poor population may characterize the primordial stellar halo and the net retrograde rotation could then reflect an underestimate in our adopted local standard of rest circular velocity Θ₀. If Θ₀ is ≈240 km s⁻¹, then the metal-poor component has no rotation and there is a net prograde rotation signal of ≈45 km s⁻¹ in the metal-rich component. There is reasonable evidence that the Milky Way globular cluster and satellite galaxy systems are rotating with ⟨vφ⟩ ≈ 50 and 40 km s⁻¹, respectively. Furthermore, a stronger signal is found for the satellite galaxies when the angular momentum vector of the satellites is inclined with respect to the normal of the disc. The dwarf spheroidal satellites of M31 exhibit prograde rotation relative to the M31 disc with ⟨vφ⟩ ≈ 40 km s⁻¹. We postulate that this group of dwarf spheroidals may share a common origin. We also find strong evidence for systemic rotation in the globular clusters of M31 particularly for the most metal-rich.

Key words: galaxies: general – galaxies: haloes – galaxies: individual: M31 – galaxies: population II stars – globular clusters with [Fe/H] < −1 – dark matter – dark matter halo – rotation

1 INTRODUCTION

Our own Milky Way Galaxy and its nearest neighbour Andromeda (M31) provide testing grounds for theories of galaxy formation and evolution. Studies of local stellar populations explore the complex processes which built up the galaxies. The orbits of tracer populations bear the imprint of the infall and subsequent accretion history of the dark matter halo. In a monolithic collapse model (see e.g. Eggen, Lynden-Bell & Sandage 1962), the halo and the disc of the galaxy are drawn from the same population. Any rotational signature in the outer halo is thus aligned with the angular momentum of the disc. However, in a hierarchical picture, substructure arriving late at large radii may have little connection to the disc. Its evolution is further complicated by processes such as tidal disruption, disc shocking and dynamical friction. For example, prograde-rotating systems are more susceptible to dynamical friction than retrograde (Quinn & Goodman 1986). Norris & Ryan (1989) suggested that the subsequent disintegration of these accreted fragments by tidal forces may create a net retrograde asymmetry in the remnant stellar halo population. The presence, or absence, of a rotating signal can provide key insights into the formation history of the halo.

There have been a number of previous kinematic studies of halo populations in the Milky Way Galaxy. For example, Frenk & White (1980) found that the globular cluster system has a velocity distribution that is isotropic about a net prograde rotation (vrot ~ 60 km s⁻¹). Zinn (1985) extended this work by restricting attention to halo globular clusters with [Fe/H] < −1 and found a slightly weaker net prograde motion (vrot ~ 50 km s⁻¹). Norris (1986) used a sample of metal-poor objects ([Fe/H] < −1.2) and found evidence for weak prograde rotation, although he found no kinematic difference between the clusters and halo stars, suggesting these are part of the same population.

The isotropic velocity distribution of the globular clusters contrasts with the highly anisotropic distributions usually found for Population II stars (Woolley 1978; Hartwick 1983; Ratnatunga & Freeman 1985). Cosmological simulations generally predict increasing radial anisotropy with Galactocentric radii for halo stars (e.g. Abadi, Navarro & Steinmetz 2006) as a consequence of the
accretion of infalling structure. Observationally, the situation is less clear-cut with radially biased (e.g. Chiba & Beers 2000), isotropic (e.g. Sirko et al. 2004b) and even tangentially biased (Sommer-Larsen et al. 1997) velocity distributions claimed for the outer stellar halo.

More recently, a number of authors have advocated a dual halo structure, which suggests that the stellar halo was formed by at least two distinct phases of accretion events. The evidence includes studies of the spatial profiles (Hartwick 1987; Kinman, Suntzeff & Kraft 1994; Miceli et al. 2008), as well as kinematic studies indicating net retrograde rotation in the outer parts (Majewski 1992; Carney et al. 1996; Wilhelm et al. 1996; Kinman et al. 2007). For example, Carollo et al. (2007) claimed a dual halo structure consisting of a weakly prograde-rotating inner halo and a retrograde-rotating outer halo of lower metallicity ([Fe/H] < −2). However, this idea is inconsistent with work by Chiba & Beers (2000) on local neighbourhood stars and by Sirko et al. (2004b) on distant blue horizontal branch (BHB) stars who both find no evidence for rotation in the outer halo.

This somewhat confused picture is partly caused by the difficulties of the task. Full kinematic analyses of tracer populations are hampered by small sample sizes and lack of complete information on the phase-space coordinates. Often, work has been confined to comparatively local samples, which may not be unbiased tracers of the overall population. This, though, is beginning to change with more recent studies on BHB stars reaching out to distances of ~80 kpc (e.g. Sirko et al. 2004b; Xue et al. 2008), albeit with only the line-of-sight velocities available. In fact, several surveys have the promise to provide much larger samples of halo tracers with well-defined kinematical parameters. This includes ongoing projects like the Sloan Digital Sky Survey (SDSS; York et al. 2000) and the Sloan Extension for Galactic Understanding and Exploration (SEGUE; Newberg & Sloan Digital Sky Survey Collaboration 2003), as well as future projects like the Gaia satellite (Turon, O’Flaherty & Perryman 2005) and the Large Synoptic Survey Telescope (LSST; Ivezić et al. 2008).

There has also been a lively debate in recent years as to the possibility that the satellite galaxies of the Milky Way lie in a rotationally supported disc. The idea may be traced back to Lynden-Bell (1983), who first suggested the Magellanic Clouds, Ursa Minor and Draco may have been torn from a single progenitor, a gigantic gas-rich proto-Magellanic Cloud. Working with more complete data sets, Kroupa, Theis & Boily (2005) claimed that satellite galaxies occupy a highly inclined disc and that this is at odds with the predictions of cosmological simulations. The available proper motion measurements have been used to constrain the angular momenta orientations of the satellites (e.g. Palma, Majewski & Johnston 2002; Metz, Kroupa & Libeskind 2008), indicating evidence for some sort of coherent motion, possibly rotation. Even if true, it remains disputatious as to whether this can be reconciled within the cold dark matter framework of structure formation (Metz et al. 2008; Libeskind et al. 2009).

Rotational properties of halo populations can therefore provide clues as to their origin and evolution, and may allow us to identify associations sharing a common formation history. With this in mind, we develop some simple and flexible distribution functions (DFs) that can model rotating stellar populations embedded in dark halos. Cosmological arguments suggest that dark halos have a universal Navarro–Frenk–White (NFW) form (Navarro, Frenk & White 1996), whilst many stellar populations in the outer halo are well approximated by a power law. Section 2 provides a flexible set of simple DFs that are powers of energy $E$ and angular momentum $L$ and which can be adapted to include rotation. We apply the models to the satellite galaxy, globular cluster and BHB populations of the Milky Way (Section 3) and M31 (Section 5), with the implications of our results for the Milky Way given particular attention in Section 4. Finally, Section 6 sums up.

2 DISTRIBUTION FUNCTIONS

2.1 The even part of the distribution function

A collisionless system can be described by a phase-space DF, $F$. The probability that a star occupies the phase-space volume $\mathrm{d}^3x\,\mathrm{d}^3v$ is given by $F(x, v)\mathrm{d}^3x\,\mathrm{d}^3v$. DFs are a valuable tool for studying steady-state systems as they replace the impracticality of following individual orbits with a phase-space probability density function. The part of the DF that is even in $v_\phi$ fixes the density, whilst the part that is odd in $v_\phi$ fixes the rotational properties.

To construct the DFs, we assume a steady-state spherical potential and a density profile for our halo populations. Of course, these are tracer populations moving in an external gravitational field generated by the dark matter halo rather than the self-consistent density generated through Poisson’s equation. For simplicity, we use simple power-law profiles for the density and potential, namely $\rho \propto r^{-\alpha}$ and $\Phi \propto r^{-\gamma}$, where $\alpha$ and $\gamma$ are constants.

The density profile of dark matter haloes in cosmological simulations resemble the NFW profile (Navarro et al. 1996). Exterior to $r \approx 20$ kpc, we can approximate the NFW potential by a power-law profile, as shown in Fig. 1. Here, we have used one of the NFW models applicable to the Milky Way from Klypin et al. (2002), and have normalized the power-law profile to reproduce the local escape speed found by Smith et al. (2007). We see that a power law with index $\gamma = 0.5$ is a good approximation at large radii ($r > 20$ kpc). At small radii, the approximation breaks down, but in this regime, the bulge and disc components become important. In any case, our main application is to trace populations that reside far out in the halo. The dark halo mass within a given...
radius is

\[ M(<r) = \frac{\Phi_0 R_{\odot}^{1/2}}{2G} r^{3/2}, \]

where \( \Phi_0 \) is the normalization at the solar radius \( R_{\odot} \). For a virial radius of 250 kpc, the halo mass enclosed is \( \approx 8 \times 10^{11} M_{\odot} \), in good agreement with estimates for the Milky Way Galaxy and M31 (e.g. Evans & Wilkinson 2000; Battaglia et al. 2005; Xue et al. 2008; Watkins, Evans & An 2010).

Previous authors have adopted power-law density profiles for halo populations with \( \alpha = 2 < \alpha < 5 \). For example, Harris (1976), Zinn (1985) and Djorgovski & Meylan (1994) find a power law with \( \alpha = 3.5 \) is a good fit to the Milky Way globular cluster populations. Classical studies have found \( \alpha = 3.5 \) for stellar populations in the Milky Way halo (e.g. Freeman 1987). More recently, Bell et al. (2008) find values of \( \alpha \) in the range 2–4, although they caution against the use of a single power law due to the abundant substructure in the stellar halo. The density profile of the system of Milky Way satellite galaxies is poorly known due to the small sample size and incompleteness at large radii. Evans & Wilkinson (2001) find \( \alpha = 3.4 \) is a good approximation for \( r > 20 \) kpc, whilst Watkins et al. (2010) adopt a power law of \( \alpha = 2.6 \). Similar profiles have been used for the M31 halo populations. Crampton et al. (1985) argue that the radial profile of the M31 globular cluster system is similar to that of the Milky Way and so it is reasonable to adopt the same power law. Evans & Wilkinson (2000) and Watkins et al. (2010) use \( \alpha \) values of 3.5 and 2.1, respectively, for the M31 satellites. As a convenient summary of all this work, we will use a density power-law index of \( \alpha = 3.5 \), but we discuss the effects of varying \( \alpha \) in Section 3.

Armed with these simple forms for the potential and density, we can give the velocity distribution in terms of the binding energy \( E = \Phi(r) - \frac{1}{2}(v_x^2 + v_y^2 + v_z^2) \) and the total angular momentum \( L = \sqrt{L_x^2 + L_y^2 + L_z^2} \).

\[ F_{\text{even}}(E, L) \propto L^{-2\beta} f(E), \]

where

\[ f(E) = E^{(\beta(y-2)/y+(\alpha+2)/y-3/2)}. \]

Here, \( \beta \) is the Binney anisotropy parameter (Binney & Tremaine 1987), namely

\[ \beta = 1 - \frac{\langle v_x^2 \rangle}{\langle v_y^2 \rangle}, \]

which is constant for the DFs of the form of equation (2). These DFs are discussed in greater detail in Evans, Hafner & de Zeeuw (1997).

### 2.2 The odd part of the distribution function

So far, our DFs describe non-rotating populations embedded in dark haloes. We now devise an odd part to the DF which generates a one-parameter family of rotating models

\[ F_{\text{odd}} = (1 - \eta) \tanh(L_z/\Delta) F_{\text{even}}, \]

where \( \eta \) is a constant. The case \( \eta = 0 \) describes maximum prograde rotation, whilst \( \eta = 2 \) describes maximum retrograde rotation. Here, \( \Delta \) is a ‘smoothing’ parameter to ease numerical calculations and soften the Heaviside function.

To illustrate the effects of the parameter \( \eta \), we compute the mean streaming velocity \( \langle v_\phi \rangle \), which is analytic for \( \gamma = 0.5 \)

\[ \langle v_\phi \rangle = \frac{2^{3/2} \Gamma(3/2) - \beta \Gamma(2\alpha - 4\beta + 1)\Gamma(1 - \eta)\Phi(r)^{1/2}}{\pi \Gamma(1 - \beta) \Gamma[2\alpha - 4\beta + (3/2)]}. \]

### Table 1

| \( \eta \) | \( \beta \) | \( \langle v_\phi, 50 \text{ kpc} \rangle \text{ km s}^{-1} \) | \( \langle v_\phi, 100 \text{ kpc} \rangle \text{ km s}^{-1} \) |
|---|---|---|---|
| 0.0 | (−0.5, 0, 0.5) | (82, 72, 53) | (69, 61, 45) |
| 0.5 | (−0.5, 0, 0.5) | (41, 36, 27) | (34, 30, 22) |
| 1.0 | (−0.5, 0, 0.5) | (0, 0, 0) | (0, 0, 0) |
| 1.5 | (−0.5, 0, 0.5) | (−41, −36, −27) | (−34, −30, −22) |
| 2.0 | (−0.5, 0, 0.5) | (−82, −72, −53) | (−69, −61, −45) |

### Figure 2

The mean streaming velocity \( \langle v_\phi \rangle \) as a function of Galactocentric distance for \( \gamma = 0.5 \) and \( \alpha = 3.5 \). Solid and dotted lines correspond to maximum prograde and retrograde rotation, respectively. The profile flattens at large radii. Blue, red and green lines represent isotropic, radial and tangential velocity distributions, respectively.

Table 1 lists \( \langle v_\phi \rangle \) values at \( r = 50, 100 \) kpc for three different anisotropy parameters. Fig. 2 shows the radial profile of the streaming motion for maximum prograde (solid line) and maximum retrograde (dotted line) distributions.

### 2.3 Properties

It is rare that we possess full 6D phase-space information for any star. However, we can still use a DF by marginalizing over the unknown components. For example, consider a case where the spatial position and line-of-sight velocity are well known, but the proper motions are uncertain. In this case, we marginalize over \( v_l \) and \( v_b \) to obtain the line-of-sight velocity distribution (LOSVD):

\[ F(l, b, d, v_{los}) = \int \int F(l, b, d, v_l, v_b) dv_l dv_b. \]

Once \( \gamma \) is fixed as 0.5, there remain the free parameters, \( \beta, \alpha \) and \( \eta \).

Some properties of the DFs are shown in Fig. 3. The top left-hand panel shows \( F(l, b, d, v_{los}) \) as a function of \( v_{los} \) at three different distances from the Sun (for the case \( \alpha = 3.5 \)). An arbitrary line of sight toward the Leo constellation is chosen for illustration, \( l = (230^\circ, 50^\circ) \). Closer to the Galactic Centre the escape velocity is larger, so the velocity distributions are broader. Tangential orbits (\( \beta = 0 \)) have narrower radial velocity and broader tangential velocity distributions. The reverse is true for radial orbits (\( \beta > 0 \)).

For distant objects in the Milky Way, \( v_{los} \approx v_t \), and so the LOSVD reflects the radial distribution. At small radii, the trend is not so
Figure 3. Top left-hand panel: the dependence of the DF on $v_{los}$ at three different distances in the non-rotating case. A random line of sight is chosen (towards the Leo constellation) and the density power law is set to $\alpha = 3.5$. Blue, red and green lines represent isotropic, radial and tangential velocity distributions, respectively. Top right-hand: the DF for three different density profile power laws in the non-rotating case. The distance is fixed at $d = 80$ kpc. Middle left-hand panel: the LOSVD when rotation is included. A prograde-rotating case is shown ($\eta = 0.1$) for two different longitudes. At large distances, little difference is seen from the non-rotating case. Middle right-hand panel: as the adjacent panel, but now the distance is fixed to $d = 30$ kpc. More pronounced rotation is seen at smaller distances. Bottom left-hand panel: the line-of-sight DF for the prograde case at three different distances. The same line of sight as the top panels is chosen. Very small deviations from a non-rotating distribution are seen. The tangential and radial velocity distributions are shown by green and red lines, respectively. Bottom right-hand panel: The longitudinal velocity, $v_l$, distribution with the same parameters as the adjacent panel. Rotation is much more apparent in this case and the distribution is almost entirely skewed to negative $v_l$. 

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simple and depends on the particular line of sight in question. The top right-hand panel of Fig. 3 illustrates the dependence of $F(l, b, d, v_{hel})$ on the power-law index of the density profile, $\alpha$. In a given gravitational potential, more extended tracer populations (smaller $\alpha$) exhibit larger velocity dispersions than more centrally concentrated ones.

The middle panels of Fig. 3 show the changes to the LOSVVs caused by the introduction of rotation. At large distances ($d \sim 80$ kpc), the rotating distribution is hardly distinguishable from the non-rotating case ($v_{hel} \approx v_{r}$). As expected, radially biased velocity distributions show the smallest deviation from the non-rotating case, but even a tangentially biased system may only show small differences. At smaller distances ($d \sim 30$ kpc), the profile depends on the particular line of sight as illustrated in the middle right-hand panel.

The bottom panels show the LOSVD and the longitudinal velocity distribution for prograde-rotating systems ($\eta = 0.1$). We see that with just the line-of-sight velocity, the rotation of a system may be difficult to constrain. In particular, if the line-of-sight component of velocity is largely due to the radial component, then we can only poorly constrain rotation. However, applications where the line-of-sight velocity has significant contributions from the tangential velocity components, as for example in the case of M31, can give a more robust prediction for the rotation. The bottom right-hand panel shows the distribution as a function of $v_r$. In this case, the distributions show much more pronounced differences from the non-rotating case. For this particular line of sight and with $\eta = 0.1$, the distribution is almost entirely skewed to negative $v_r$. This has important implications for the relevance of accurate proper motion measurements. The components of motion perpendicular to the line of sight can give conclusive evidence for rotation, whilst the deductions from the line-of-sight velocities rely heavily on the particular line of sight.

3 APPLICATIONS: THE MILKY WAY GALAXY

In this section, we apply our DFs to halo populations in the Milky Way Galaxy. Observed heliocentric velocities are converted to Galactocentric ones by assuming a circular speed of 220 km s$^{-1}$ at the position of the Sun ($R_0 = 8.5$ kpc) with a solar peculiar motion ($U, V, W) = (11.1, 12.24, 7.25)$ km s$^{-1}$ (recently updated by Schönrich, Binney & Dehnen 2010). Here, $U$ is directed towards the Galactic Centre, $V$ is positive in the direction of Galactic rotation and $W$ is positive towards the north Galactic pole.

We set the power-law indices for the potential and density to $\gamma = 0.5$ and $\alpha = 3.5$, respectively. We allow the anisotropy $\beta$ and rotation $\eta$ parameters to be estimated by maximum likelihood analysis of the data. For example, when we have full distance information and the line-of-sight velocity, we construct the likelihood function from the LOSVD:

$$L(\eta, \beta) = \prod_{i=1}^{N} \log F(l_i, b_i, d_i, v_{hel}, \eta, \beta),$$

where $N$ is the number of objects in the population. Equation (8) gives the $2D$ likelihood as a function of $\beta$ and $\eta$. As we are mainly interested in constraining rotation, we sometimes fix $\beta$ and find the likelihood as a function of $\eta$.

3.1 Milky Way BHB stars

BHB stars are excellent tracers of halo dynamics as they are luminous and have an almost constant absolute magnitude (within a certain colour range). We construct a sample of BHBs from the Sloan Digital Sky Survey (SDSS) Data Release 7 (DR7). To select BHBs, we impose constraints on the (extinction corrected) $u - g$ and $g - r$ colours, the surface gravity ($g_*$) and the effective temperature ($T_{eff}$), namely

$$0.8 < u - g < 1.4,$$

$$-0.4 < g - r < 0,$$

$$2 < \log(g_*) < 4,$$

$$7250 < T_{eff}/K < 9700.$$

These cuts are similar to those used by previous authors (e.g. Yanny et al. 2000, Sirko et al. 2004a) and are implemented to minimize contamination by blue stragglers and main-sequence stars. We only consider stars with $|z| > 4$ kpc, as we wish to exclude disc stars. Xue et al. (2008) compiled a sample of 2558 BHB stars from SDSS DR6 using Balmer line profiles to select suitable candidates. Our larger sample (we use DR7) of 5525 stars includes $\approx 88$ per cent of the Xue sample.

Heliocentric distances are evaluated photometrically by assuming BHBs have an absolute magnitude of $M_g = 0.7$ in the $g$ band.\footnote{1 We check that changing our assumed absolute magnitude from $M_g = 0.7$ to 0.55 makes a negligible difference to our dynamical analysis.} The absolute magnitudes of BHB stars are slightly affected by temperature and metallicity (e.g. Sirko et al. 2004a), but we expect that this variation makes a negligible difference to our distance estimates. We compare our distance estimates to those of Xue et al. (2008), who take into account such variations, and find agreement to within 10 per cent.

We remove contamination of stars belonging to the Sagittarius dwarf galaxy by masking out tracers lying in the region of the leading and trailing arms. Our final sample contains 3549 BHB stars (with $r > 10$ kpc) and so provides a statistically representative population to study the outer stellar halo. The heliocentric velocity errors are $\approx 5$ km s$^{-1}$ on average, at larger radii the error increases due to the decreasing brightness of the source. The maximum error in the velocity is $\approx 20$ km s$^{-1}$.

We use the metallicities derived from the Wilhelm, Beers & Gray (1999) analysis (the “WBG” method) as this method was adopted specifically for BHB stars. The method uses the Ca K lines as a metal abundance indicator and is applicable in the range $-3 < [\text{Fe/H}] < 0$. Only a small fraction ($N \sim 300$) of stars do not have assigned metallicities or are outside the applicable metallicity range.

Fig. 4 shows that the overall population (purple contour) has slight net retrograde rotation ($\eta = 1.1$) and has an almost isotropic distribution. By splitting the sample into metal-poor ([Fe/H] $< -2$, blue contours) and ‘metal-rich’ ([Fe/H] $> -2$, red contours) subsamples, we find retrograde and prograde signals for the two subsets, respectively. The mean streaming motions for the metal-poor and metal-rich samples are $(v_{hel} = -35 \pm 10$) $/(r/10$kpc)$^{-1/4}$ km s$^{-1}$ and $(v_{hel} = 21 \pm 11$) $/(r/10$kpc)$^{-1/4}$ km s$^{-1}$, respectively. We remove the radial dependence by averaging over the volume interval $(10 < r/kpc < 50)$ to find $(v_{hel} = -25 \pm 7$) km s$^{-1}$ and $(v_{hel} = 15 \pm 8$) km s$^{-1}$ for the metal-poor and metal-rich populations, respectively. These results can be compared to Carollo et al. (2007) who find a rotating retrograde outer halo and a weakly prograde-rotating inner halo. Our analysis only applies to the outer halo, but instead of a single population with net retrograde rotation, we find evidence for two separate populations split by metallicity (at $[\text{Fe/H}] \sim -2$). In agreement with Carollo et al. (2007); who focus...
This could be a part of a scientific paper discussing the rotation of halo stars in the Milky Way and M31. The figure (Fig. 4) shows 1σ confidence regions for Milky Way BHB stars in the η, β plane from a maximum likelihood analysis. Arrows indicate prograde, retrograde, tangential, and radial distributions. The overall population (N = 3549 with r > 10 kpc) is shown by the purple filled contour. Metal-poor ([Fe/H] < −2, N = 1135) and metal-rich ([Fe/H] > −2, N = 2125) subsamples are shown by blue and red contours, respectively. The paler shades show the radial bin 25 < r/kpc < 50, whilst the darker shades show the radial bin 10 < r/kpc < 25.

Figure 4. 1σ confidence regions for Milky Way BHB stars in the η, β plane from a maximum likelihood analysis. Arrows indicate prograde, retrograde, tangential, and radial distributions. The overall population (N = 3549 with r > 10 kpc) is shown by the purple filled contour. Metal-poor ([Fe/H] < −2, N = 1135) and metal-rich ([Fe/H] > −2, N = 2125) subsamples are shown by blue and red contours, respectively. The paler shades show the radial bin 25 < r/kpc < 50, whilst the darker shades show the radial bin 10 < r/kpc < 25.

on halo stars within the solar circle) we find evidence for a net retrograde-rotating metal-poor halo component, but we find that the outer halo also contains a more metal-rich, slightly prograde-rotating component.

We can make a rough estimate of the luminosity associated with these metal-rich and metal-poor remnants assuming 40 per cent of the metal-poor sample (η ∼ 1.4, N_{metal-poor} = 1135) and 20 per cent of the metal-rich sample (η ∼ 0.8, N_{metal-rich} = 2125) are rotating. The fraction of rotating stars can be scaled to the overall population by calculating the total number of BHBs in a spherical volume. This requires a normalization factor for our density profile (ρ ∝ r^{−3.5}).

We adopt the normalization applicable to RR Lyrae stars found by Watkins et al. (2009) and assume the ratio of BHBs to RR Lyrae is approximately 2:1. Finally, using photometry for globular clusters given in An et al. (2008), we find the relation N_{BHB}/L ∼ 10^{−3} L⊙/M⊙ where N_{BHB} is found by applying a cut in colour–colour space – see equation 9. We find for both the metal-poor and metal-rich rotating populations a luminosity L ∼ 10^{10} L⊙. For a mass-to-light ratio of M/L ∼ 10 (appropriate for luminous satellites – see fig. 9 in Mateo 1998), this gives a total mass estimate of M ∼ 10^{10} M⊙. This rough calculation suggests that these rotating signals could be remnants of two separate accretion events caused by massive satellites with different metallicities and orbital orientations.

The different shaded contours in Fig. 4 show different radial bins. The paler shades are for the range 25 < r/kpc < 50, whilst the darker shades are for the range 10 < r/kpc < 25. Splitting the sample into radial bins not only shows the rotation signal is present at all radii (albeit with less confidence at greater distances due to smaller numbers), but also that the velocity distribution becomes more radially biased with increasing Galactocentric radii. This result is in agreement with the findings of cosmological simulations (e.g. Diemand, Kuhlen & Madau 2007; Sales et al. 2007). Stars populating the outer halo are likely remnants of merger events and therefore can be on eccentric orbits. However, the anisotropy parameter β is dependent on the adopted density profile (whereas the rotation parameter η is independent). More centrally located populations (larger α) exhibit narrower velocity dispersions (see Section 2). To compensate for the narrower velocity dispersion, the unknown tangential distribution shrinks as we only have a measurement for the line-of-sight velocity. Hence, the distribution becomes more radially anisotropic (β increases) when we adopt steeper density power laws. This is shown in Fig. 5 for two radial bins. To break this degeneracy we require a full analysis of the density profile of the BHB sample. As our main result regarding rotation is unaffected we defer this task to a future paper.

Evidence for substructure in the metal-rich sample is shown in Fig. 6. Here, we show the line-of-sight velocity dispersion, σ_{los}, as a function of Galactocentric radii. We formulate error bars by assuming Gaussian distributed errors and apply a maximum likelihood routine to find the 1σ deviations. There is an obvious ‘cold’ structure in the metal-rich sample for 20 < r/kpc < 30. This could be evidence for a shell-type structure caused by a relatively recent accretion event. The lack of such a feature in the metal-poor sample suggests that the net retrograde signal is not a consequence of a single accretion event. The dichotomous nature of the outer halo may reflect two populations with very different origins. This is discussed further in Section 4.

We note that a larger sample of BHB stars extending to larger Galactocentric distances will be invaluable in studying the outer reaches of the stellar halo. To date very few tracers are available,
3.2 Milky Way globular clusters

The kinematics of the Milky Way globular clusters have been studied by a number of authors (e.g. Frenk & White 1980; Zinn 1985). We apply the methods adopted in the previous section to model the halo globular clusters. Using the data taken from Harris (1996), we restrict attention to those at galactocentric distances $r > 10 \text{kpc}$.

With line-of-sight velocities alone, our sample of 41 globular clusters poorly constrains $\beta$ and $\eta$. We improve this analysis using the proper motion measurements from Dinescu, Girard & van Altena (1999) and Casetti-Dinescu et al. (2007), which include 15 of our halo clusters (see Table 2). We use a similar procedure to Wilkinson & Evans (1999) and convolve our probabilities with an error function. Equation (7) becomes

$$F(l, b, d, v_{\text{obs}}) = \int \int E_l(v)E_b(v)\, dv_1\, dv_2,$$

where $E_l(v)$ is the error function. We assume the Lorentzian given by

$$E_l(v) = \frac{2\sigma_v^2}{2\pi \sigma_v^2 + (v - v_{\text{obs}})^2},$$

where $\sigma_v$ is related to the published error estimate by $\sigma_v = 0.477 \sigma_{\text{mean}}$. The properties of such functions are discussed further in appendix A of Wilkinson & Evans (1999). We show in the left-hand panel of Fig. 7 that the halo clusters have a mildly radial distribution ($\beta = 0.5^{+0.1}_{-0.3}$) and net prograde rotation ($\eta = 0.3^{+0.35}_{-0.3}$). We find a mean streaming motion of $\langle v_{\phi} \rangle = (58 \pm 27) (r/10 \text{kpc})^{-1/4} \text{km s}^{-1}$ which evaluates to $\langle v_{\phi} \rangle \sim (60-50) \text{km s}^{-1}$ in the range $r = (10-20) \text{kpc}$. This agrees with previous authors (e.g. Frenk & White 1980; Zinn 1985) who have found that the halo globular clusters are primarily pressure supported, but show weak rotation with $v_{\text{rot}} \sim 50-60 \text{km s}^{-1}$.

The right-hand panel of Fig. 7 shows the $v_{\phi}$ velocity components of the globular clusters overplotted on a mildly radial model for $\langle v_{\phi} \rangle(r)$. The majority of the globular clusters have positive $v_{\phi}$ and hence the net streaming motion is prograde. However, five of the halo globular clusters have negative $v_{\phi}$. As our sample only consists of 15 objects, we cannot conclude that this net prograde rotation is ubiquitous for the whole population. There is no obvious correlation between rotational velocity and metallicity, suggesting independent accretion events rather than dissipative collapse as the formation mechanism.

The majority of the halo globular clusters in our sample have metallicities between $-2 < \text{[Fe/H]} < -1$ and Galactocentric radii in the range $10 < r/\text{kpc} < 20$ (with the notable exception of Pal 3). It is interesting that these properties are in common with the relatively metal-rich halo BHB stars, which also exhibit net prograde rotation (albeit a weaker signal). We suggest that some of the globular clusters with positive $v_{\phi}$ may share a common accretion history with these relatively metal-rich field halo stars.

3.3 Milky Way satellites

Our final application focusing on our own Milky Way Galaxy looks at the satellite galaxies. Fig. 8 shows the result of the maximum likelihood analysis keeping the velocity anisotropy fixed at $\beta = 0$. We have split the satellites into ultrafaint ($L \sim 10^{-2} - 10^{-1} \text{L}_\odot$) and classical ($L \sim 10^3 - 10^4 \text{L}_\odot$) samples (see Tables 3 and 4). There is some controversy as to whether these groups are separate populations or just the bright and faint components of a single population. We can see from Fig. 8 that the rotation is poorly constrained. The 1σ confidence limit (horizontal dotted line) encompasses non-rotating,
Table 2. The Milky Way halo globular cluster sample with available proper motions. We give the Galactocentric radii \( r \) [note we correct the Harris (1996) values to a solar position of \( R_\odot = 8.5 \) kpc], the metallicity \([\text{Fe/H}]\), the heliocentric velocity, \( v_h \), the heliocentric rest frame proper motions in right ascension and declination and the rotational velocity, \( v_\phi \).

| Name       | \( r \) (kpc) | \([\text{Fe/H}]\) | \( v_h \) (km s\(^{-1}\)) | \( \mu_\alpha \cos(\delta) \) (mas yr\(^{-1}\)) | \( \mu_\delta \) (mas yr\(^{-1}\)) | \( v_\phi \) (km s\(^{-1}\)) | Ref  |
|------------|---------------|-------------------|--------------------------|---------------------------------|---------------------------------|--------------------------|-----|
| NGC 288    | 11.8          | -1.24             | -46.6                    | 4.40 ± 0.23                     | -5.62 ± 0.23                   | -27 ± 18                 | 1.2 |
| NGC 1851   | 17.2          | -1.26             | 320.9                    | 1.28 ± 0.68                     | 2.39 ± 0.65                    | 134 ± 29                 | 1.2 |
| NGC 1904   | 18.9          | -1.54             | 207.5                    | 2.12 ± 0.64                     | -0.02 ± 0.64                   | 83 ± 29                  | 1.2 |
| NGC 2298   | 16.0          | -1.85             | 148.9                    | 4.05 ± 1.00                     | -1.72 ± 0.98                   | -27 ± 30                 | 1.2 |
| NGC 2808   | 11.2          | -1.37             | 93.6                     | 0.58 ± 0.45                     | 2.06 ± 0.46                    | 82 ± 16                  | 1.3 |
| NGC 4147   | 21.1          | -1.83             | 183.2                    | -1.85 ± 0.82                    | -1.30 ± 0.82                   | 67 ± 65                  | 1.2 |
| NGC 4590   | 10.3          | -2.06             | -95.2                    | -3.76 ± 0.66                    | 1.79 ± 0.62                    | 294 ± 30                 | 1.2 |
| NGC 5024   | 19.0          | -2.07             | -79.1                    | 0.50 ± 1.00                     | -0.10 ± 1.00                   | 240 ± 85                 | 1.2 |
| NGC 5272   | 12.1          | -1.57             | -148.6                   | -1.10 ± 0.51                    | -2.30 ± 0.54                   | 105 ± 24                 | 1.2 |
| NGC 5466   | 17.0          | -2.22             | 107.7                    | -4.65 ± 0.82                    | 0.80 ± 0.82                    | -63 ± 64                 | 1.2 |
| NGC 6934   | 12.4          | -1.54             | -411.4                   | 1.20 ± 1.00                     | -5.10 ± 1.00                   | -67 ± 60                 | 1.2 |
| NGC 7078   | 10.5          | -2.22             | -107.5                   | -0.95 ± 0.51                    | -0.63 ± 0.50                   | 120 ± 25                 | 1.2 |
| NGC 7089   | 10.4          | -1.62             | -53.3                    | 5.90 ± 0.86                     | -4.95 ± 0.86                   | -84 ± 41                 | 1.2 |
| Pal 3      | 92.9          | -1.66             | 83.4                     | 0.33 ± 0.23                     | 0.30 ± 0.31                    | 146 ± 95                 | 1.2 |
| Pal 5      | 17.8          | -1.38             | -55.0                    | -1.78 ± 0.17                    | -2.32 ± 0.23                   | 42 ± 34                  | 1.2 |

References: (1) Harris (1996); (2) Dinescu et al. (1999); (3) Casetti-Dinescu et al. (2007).

Figure 7. Left-hand panel: the confidence contours for Milky Way halo globular clusters in the \( \eta, \beta \) plane evaluated from a 2D maximum likelihood analysis. Arrows illustrate prograde, retrograde, radial and tangential distributions. We use \(- \ln (1 - \beta)\) on the y-axis to make the ranges occupied by radial and tangential models symmetric. The Milky Way globular clusters with available proper motions \((N = 15)\) show evidence for prograde rotation \((\beta \sim 0.3)\) and a mildly radial velocity distribution \((\beta \sim 0.5)\). Right-hand panel: the streaming motion as a function of Galactocentric radius for a mildly radial distribution \((\beta = 0.5)\). Different line styles represent different rotation parameters \((\eta)\). Overplotted are the \( v_\phi \) velocity components of the Milky Way globular clusters with available proper motions. The points are colour coded according to metallicity, black being the most metal poor \(([\text{Fe/H}] \sim -2.2)\) and red being the most metal rich \(([\text{Fe/H}] \sim -1.2)\). There is no obvious correlation with metallicity, but the two clusters with particularly large positive \( v_\phi = (200–300 \text{ km s}^{-1}) \), NGC 4590 and 5024, are also metal poor \(([\text{Fe/H}] < -2)\). Note that ~5 of the globular clusters have negative \( v_\phi \), but the majority have positive \( v_\phi \). As there are only 15 objects in the sample, the net prograde motion may not be representative of the whole population. Pal 3 is not shown as its distance of \( 92.9 \text{ kpc} \) is beyond the range of the plot, but note that it too has a positive \( v_\phi \) (albeit with large formal uncertainties, \( 146 \pm 95 \text{ km s}^{-1})\).

With these extra constraints on the tangential velocity components, the maximum likelihood method gives evidence for prograde rotation \((\eta = 0.5^{+0.4}_{-0.2}, \beta = -1.5_{-0.7}^{+0.9})\). Evaluating equation (6) gives \( \langle v_\phi \rangle = (69 \pm 42) (r/10 \text{ kpc})^{-1/2} \text{ km s}^{-1})\). Averaging over the volume interval \((10 < r/\text{kpc} < 150)\) gives \( \langle v_\phi \rangle = (38 \pm 23) \text{ km s}^{-1}\). The right-hand panel of Fig. 9 shows \( v_\phi \) for the satellites with proper motion data overplotted on a tangential model for \( (v_\phi(r)) \) (see Fig. 2). Most of the satellites have prograde rotation components, although the Fornax and Ursa Minor satellites show retrograde rotation.

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Figure 8. Maximum likelihood analysis of the rotation parameter, $\eta$, for Milky Way satellites. The velocity anisotropy is kept fixed at $\beta = 0$. The y-axis, $\exp[-(L_\eta - L_{\eta,\text{max}})]$, is the reduction of the likelihood for a particular $\eta$ value with respect to the maximum likelihood. The red (solid) and blue (dashed) lines represent the classical and ultrafaint satellites, respectively. Rotation is poorly constrained in both cases.

Table 3. The properties of the ultrafaint Milky Way satellites. We give the Galactic coordinates ($l$, $b$), the heliocentric distance $d$ and the heliocentric velocity $v_h$. 

| Name       | $l$ (°) | $b$ (°) | $d$ (kpc) | $v_h$ (km s$^{-1}$) | Ref |
|------------|---------|---------|-----------|---------------------|-----|
| Boo I      | 358.1   | 69.6    | 62.0      | 99.0                | 1   |
| Boo II     | 353.7   | 68.9    | 46.0      | −117.0              | 2   |
| Can Ven I  | 74.3    | 79.8    | 224.0     | 30.9                | 3   |
| Can Ven II | 113.6   | 82.7    | 151.0     | −128.0              | 3   |
| Coma       | 241.9   | 83.6    | 44.0      | 98.1                | 3   |
| Hercules   | 28.7    | 36.9    | 138.0     | 45.0                | 3   |
| Leo IV     | 265.4   | 56.5    | 158.0     | 132.3               | 3   |
| Leo V      | 261.9   | 58.5    | 180.0     | 173.3               | 3   |
| Segue I    | 220.5   | 50.4    | 23.0      | 206.0               | 5   |
| Segue II   | 149.4   | −38.1   | 35.0      | −39.2               | 6   |
| Ursa Maj II| 152.5   | 37.4    | 32.0      | −116.5              | 3   |
| Willman I  | 158.6   | 56.8    | 38.0      | −12.3               | 1   |

References: (1) Martin et al. (2007); (2) Koch et al. (2009); (3) Simon & Geha (2007); (4) Belokurov et al. (2008); (5) Geha et al. (2009); (6) Belokurov et al. (2009).

Watkins et al. (2010) recently reported $\beta = 0.44$ for the Milky Way satellites based on results of simulations by Diemand et al. 2007. However, based on the proper motion data, the same authors find $\beta \approx −4.5$, favouring tangential orbits. Our result also favours tangential orbits (in agreement with Wilkinson & Evans (1999) who find $\beta \approx −1$).

The orbits of the satellites for which we have all velocity components are preferentially polar ($v_\phi$ is the largest velocity component). This has been noted in earlier work (e.g. Zaritsky & Gonzalez 1999) and has led to the suggestion that the Milky Way satellites may occupy a highly inclined disc of satellites (Palma et al. 2002; Kroupa et al. 2005; Metz, Kroupa & Jerjen 2007). We have chosen the $L_\phi$ angular component of the ensemble of satellites to be aligned with that of the disc of the Milky Way. As an inset in the left-hand panel of Fig. 9, we show how the apparent rotation changes if we introduce a tilted angular momentum vector for the ensemble of satellite galaxies ($−90° < \theta < 90°$). Note that $\theta = 0$ corresponds to alignment with the $L_\phi$ angular momentum vector of the Milky Way disc. We find more pronounced (prograde) rotation when $\theta = −50° ± 15°$. This result is not surprising considering we find preferentially polar orbits, but does not necessarily mean the satellites occupy a rotationally supported disc. We also show the approximate tilt angle found by Metz et al. (2007) of $\theta \approx −78°$ (dotted line). The authors find the spatial distribution of the satellites is best described by a highly inclined disc. Whilst our results favour a slightly less inclined plane, it is interesting that the deductions from both a kinematic and spatial analysis broadly agree. However, without more accurate proper motion measurements the disc of satellites hypothesis cannot be rigorously tested.

4 THE LOCAL STANDARD OF REST

Our interpretation of any rotation signal in the Milky Way stellar halo depends on our assumed local standard of rest rotational velocity ($\Theta_0$). The International Astronomical Union (IAU) recommend a value of $\Theta_0 = 220$ km s$^{-1}$. In practice, estimates of the rotation speed in the literature vary between 184 km s$^{-1}$ (Olling & Merrifield 1998) and 272 km s$^{-1}$ (Méndez et al. 1999). Many of these estimates are confined to regions within the solar neighbourhood and rely on assuming a value for the Galactocentric distance ($R_0$).

An abundance of evidence (net rotation, extent, metallicity, velocity, anisotropy, dispersion profile) suggests the relatively metal-rich BHB population of the Milky Way halo is associated with the accretion of a massive satellite. The low metallicity and flat velocity dispersion profile of the metal-poor population argue against an association with a single accretion event. We infer that this metal-poor population reflects the ‘primordial’ metal-poor halo. The net retrograde rotation may simply be the result of an underestimate of the local standard of rest rotational velocity. In Fig. 10 we show the effect of varying $\Theta_0$ on our results for the Milky Way halo BHB population (see Fig. 4). Increasing our adopted $\Theta_0$ value removes any retrograde signal in the metal-poor population and enhances the net prograde signal for the metal-rich population. We can provide functional forms for the rotation signal of the two components by fitting a simple linear relation to the adopted local standard of rest value:

$$\langle v_\phi \rangle_{\text{poor}} = \begin{cases} 275 & \Theta_0 \\ 220 \end{cases} - 300 \text{ km s}^{-1},$$

$$\langle v_\phi \rangle_{\text{rich}} = \begin{cases} 330 & \Theta_0 \\ 220 \end{cases} - 315 \text{ km s}^{-1},$$

$$190 < \Theta_0 / \text{km s}^{-1} < 250.$$

Here we have removed the dependence on Galactocentric radii of $\langle v_\phi \rangle$ (see equation 6) by integrating over the appropriate volume interval ($10 < r / \text{kpc} < 50$). If we assume the metal-poor halo component has no net rotation, then we can infer an independent estimate for the local standard of rest rotational velocity of $\Theta_0 \approx 240$ km s$^{-1}$.

An upward revision of the commonly adopted circular speed of 220 km s$^{-1}$ agrees with recent work by Reid et al. (2009) and Bovy, Hogg & Rix (2009) based on the kinematics of masers found in massive star-forming regions of the Milky Way. Reid et al. (2009)

2 There is a typo in the abstract of Metz et al. (2007) where an inclination angle of 88° is given instead of the (correct) value of 78°.
fit for $R_0$ and $\Theta_0$ simultaneously using kinematic and spatial information on sources well beyond the local solar neighbourhood and established a circular rotation speed, $\Theta_0 \approx 250$ km s$^{-1}$. Bovy et al. (2009) re-analysed the maser tracers using less restrictive models and found a rotation speed of $\Theta_0 \approx 240$–250 km s$^{-1}$. They confirm that there is no conflict between recent determinations of the circular rotation speed based on different methods (e.g. orbital fitting of the GD-1 stellar stream; see Koposov, Rix & Hogg 2010) and quote a combined estimate of $\Theta_0 \approx 240$ km s$^{-1}$.

Note that Carollo et al. (2007) argued that the net retrograde signal in the outer halo ($r > 10$ kpc) is due to dynamical friction effects. Quinn & Goodman (1986) show, based on the effects of dynamical friction, that fragments on retrograde orbits surrender their orbital energy to a much smaller extent than those on prograde orbits. The disintegration of many of these fragments by tidal forces may result in the formation of a halo stellar population with a net retrograde asymmetry (e.g. Norris & Ryan 1989). Hence, in this picture the metal-poor component is the accumulation of several (smaller) accretion events. However, it is questionable whether this is a plausible explanation as dynamical friction mainly affects massive satellites close to the plane of the disc. This is difficult to reconcile with the aggregation of less massive satellites which leave debris over a wide range of distances ($10 < r$/kpc $< 50$) studied in this work.

We conclude that the lack of a plausible physical explanation for a net retrograde-rotating metal-poor halo population suggests that the commonly adopted local standard of rest circular velocity needs to be revised upwards. Assuming the primordial metal-poor

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**Table 4.** The properties of the classical Milky Way satellites. Here, we give the Galactic coordinates ($l$, $b$), the heliocentric distance $d$, the heliocentric velocity $v_h$ and the heliocentric rest frame proper motions in right ascension and declination and the rotational velocity, $v_\phi$.

| Name      | $l$ ($^\circ$) | $b$ ($^\circ$) | $d$ (kpc) | $v_h$ (km s$^{-1}$) | $\mu_\alpha$ (mas cent$^{-1}$) | $\mu_\delta$ (mas cent$^{-1}$) | $v_\phi$ (km s$^{-1}$) | Ref |
|-----------|----------------|----------------|-----------|---------------------|-------------------------------|-------------------------------|------------------------|-----|
| Carina    | 260.0          | -22.2          | 101.0     | 224.0               | $22 \pm 9$                    | $15 \pm 9$                   | $68 \pm 43$            | 1.2 |
| Fornax    | 237.1          | -65.7          | 138.0     | 53.0                | $48 \pm 5$                    | $-36 \pm 4$                  | $-76 \pm 27$           | 1.3 |
| Draco     | 86.4           | 34.7           | 82.0      | -293.0              | $19 \pm 13$                   | $-3 \pm 12$                  | $17 \pm 47$            | 1.4 |
| Sagittarius | 5.6           | -14.1          | 24.0      | 140.0               | $-283 \pm 20$                | $-133 \pm 20$               | $49 \pm 22$            | 1.7 |
| Sculptor  | 287.5          | -83.2          | 79.0      | 108.0               | $9 \pm 13$                    | $2 \pm 13$                   | $126 \pm 49$           | 1.8 |
| Sextans   | 243.5          | 42.3           | 86.0      | 227.0               | $-26 \pm 41$                  | $10 \pm 44$                  | $193 \pm 153$          | 1.9 |
| SMC       | 302.8          | -44.3          | 60.0      | 158.0               | $75 \pm 6$                    | $-125 \pm 6$                | $44 \pm 16$            | 5.6 |
| Ursa Min  | 105.0          | 44.8           | 66.0      | -248.0              | $-50 \pm 17$                  | $22 \pm 16$                  | $-87 \pm 48$           | 1.1 |

References: (1) Mateo (1998); (2) Piatek et al. (2003); (3) Piatek et al. (2007); (4) Piatek, Pryor & Olszewski 2008a; (5) Karachentsev et al. (2004); (6) Piatek, Pryor & Olszewski 2008b; (7) Dinescu et al. (2005); (8) Piatek et al. (2006); (9) Walker, Mateo & Olszewski 2008; (10) Piatek et al. (2005).
Figure 10. As Fig. 4, but we show the effects of varying the local standard of rest velocity ($\Theta_0$). Metal-poor ([Fe/H] $<-2$, $N = 1135$) and metal-rich ([Fe/H] $>-2$, $N = 2125$) subsamples are shown by blue and red contours, respectively. The paler shades show an increase in the circular speed to $\Theta_0 = 250$ km s$^{-1}$, whilst the darker shades show a decrease in the circular speed to $\Theta_0 = 190$ km s$^{-1}$.

halo has no net rotation provides an independent estimate for this fundamental Galactic parameter.

5 APPLICATIONS: THE ANDROMEDA GALAXY

We now apply our analysis to the Andromeda (M31) galaxy. In this case, we transform to a coordinate system centred on M31. We define the projected distances (in angular units) along the major and minor axis, $X$ and $Y$ via

$$X = x_0 \sin(\theta_a) + y_0 \cos(\theta_a),$$

$$Y = -x_0 \cos(\theta_a) + y_0 \sin(\theta_a),$$

where $x_0$, $y_0$ are Cartesian coordinates for $\alpha$, $\delta$ with respect to the centre of M31 ($\alpha_0 = 00^h42^m44^s; \delta_0 = +41^\circ16'09''$; Cotton, Condon & Arbizzani 1999) and $\theta_a = 37.7^\circ$ (de Vaucouleurs 1958) is the position angle. We adopt the transformation outlined in appendix A of Evans & de Zeeuw (1994) to relate the projected coordinates to the galaxy coordinates (assuming an inclination angle, $i = 77.5^\circ$).

5.1 M31 satellites

The main drawback in the M31 analysis is that the distances to the satellites are not as well constrained as for the Milky Way satellites. To take this into account, we integrate the DF along the line of sight between the distance errors. The left-hand panel of Fig. 11 shows the results of the maximum likelihood analysis applied to all of the M31 satellites (see Table 5). Unlike the situation for the Milky Way satellites, our line of sight to M31 is not restricted to a predominantly radial velocity component. Fig. 11 shows evidence of prograde rotation from the line-of-sight velocity alone. We further investigate this rotating component by splitting the M31 sample into two groups based on the satellite type. These are shown by the red (dSph) and blue points (non-dSph) in Fig. 11 where we find a rotating group (dSph, red) and a non-rotating group (non-dSph, blue). The rotating subset has a rotation parameter, $\eta = 0.4^{+0.3}_{-0.3}$ and anisotropy parameter, $\beta = 0.1^{+0.3}_{-0.5}$, which corresponds to a streaming motion, $\langle v_\phi \rangle = (62 \pm 34) (r/10$ kpc$)^{-1/4}$ km s$^{-1}$. Averaging over a suitable volume interval ($10 < r$ kpc $< 200$) gives $\langle v_\phi \rangle = (32 \pm 17)$ km s$^{-1}$.

The observed line-of-sight velocities of the M31 satellites can be decomposed into radial and tangential components by making use...
of the spatial information relative to M31. These are lower limits as we only have the line-of-sight velocity component (see Metz et al. 2007). There are also large uncertainties on the distances of the satellites which permeate into the spatial coordinates with respect to M31. However, we still find it instructive to look at these approximate velocity components. The right-hand panel of Fig. 11 shows the lower limit tangential and radial velocity components for the M31 satellites. The members of the dSph rotating group are shown by red stars and the non-rotating satellites are shown by the blue circles. The majority of the rotating subgroup have a larger tangential velocity than radial velocity component.

The rotating subgroup consists entirely of dwarf spheroidal galaxies. Satellites with similar accretion histories can share common properties such as their ‘type’ (i.e. dSph) and orbital orientation. The apparent rotation of the dSph satellites of M31 suggests that these dwarfs may share a common origin.

5.2 M31 globular clusters

Over recent years, studies by several authors (e.g. Perrett et al. 2002; Galleti et al. 2007; Kim et al. 2007; Caldwell et al. 2009) have produced a rich sample of M31 globular clusters with available kinematic data. Our data derive from the Revised Bologna Catalogue (Galleti et al. 2004). Distance measurements are unavail-

Table 5. Properties of the Andromeda Satellites. Here, we give the satellite name and type (dSph = dwarf spheroidal, dIr = dwarf irregular, dE = dwarf elliptical and cE = classical elliptical), Galactic coordinates (l, b), heliocentric distance d and heliocentric velocity vh. Satellites belonging to the rotating group are starred.

| Name | Type    | l (°)  | b (°)  | d (kpc)  | v_h km s⁻¹ | Ref |
|------|---------|--------|--------|----------|-------------|-----|
| M31  | Spiral  | 121.2  | -21.6  | 785.25   | -301        | 1   |
| And I* | dSph   | 121.7  | -24.8  | 745.24   | -380        | 1   |
| And II* | dSph  | 128.9  | -29.2  | 652.18   | -188        | 1   |
| And III* | dSph | 119.4  | -26.3  | 749.24   | -355        | 1   |
| And V  | dSph   | 126.2  | -15.1  | 774.28   | -403        | 1   |
| And VI* | dSph  | 106.0  | -36.3  | 783.25   | -354        | 1   |
| And VII | dSph  | 109.5  | -9.9   | 763.25   | -307        | 1   |
| And IX* | dSph  | 123.2  | -19.7  | 765.15   | -207.7      | 2   |
| And X* | dSph   | 125.8  | -18.0  | 702.36   | -163.8      | 3.4 |
| And XI* | dSph  | 121.7  | -29.0  | 760.10   | -419.6      | 2   |
| And XII* | dSph | 122.0  | -29.5  | 830.170  | -558.4      | 2   |
| And XIII* | dSph | 123.0  | -29.9  | 910.160  | -195.0      | 2   |
| And XIV* | dSph | 123.0  | -33.2  | 740.110  | -481.1      | 5   |
| And XV* | dSph  | 127.9  | -24.5  | 770.70   | -339        | 6   |
| And XVI | dSph   | 124.9  | -30.5  | 525.50   | -385        | 6   |
| Pisces | dIr/dSph | 126.8  | -40.9  | 769.23   | -286        | 1   |
| Pegasus | dIr/dSph | 94.8   | -43.6  | 919.30   | -182        | 1   |
| NGC 147 | dE   | 119.8  | -14.3  | 675.27   | -193        | 1   |
| IC 1613 | dE   | 129.8  | -60.6  | 700.35   | -232        | 1   |
| NGC 185 | dE   | 120.7  | -14.5  | 616.26   | -202        | 1   |
| NGC 205 | dE   | 120.7  | -21.1  | 824.27   | -244        | 1   |
| IC 10  | dIr   | 119.0  | -3.3   | 825.50   | -344        | 1   |
| M32   | cE     | 121.2  | -22.0  | 785.25   | -205        | 1   |

References: (1) McConnachie & Irwin (2006); (2) Collins et al. (2009); (3) Zucker et al. (2007); (4) Kalirai et al. (2009); (5) Majewski et al. (2007); (6) Letarte et al. (2009).

of the spatial information relative to M31. These are lower limits as we only have the line-of-sight velocity component (see Metz et al. 2007). There are also large uncertainties on the distances of the satellites which permeate into the spatial coordinates with respect to M31. However, we still find it instructive to look at these approximate velocity components. The right-hand panel of Fig. 11 shows the lower limit tangential and radial velocity components for the M31 satellites. The members of the dSph rotating group are shown by red stars and the non-rotating satellites are shown by the blue circles. The majority of the rotating subgroup have a larger tangential velocity than radial velocity component.

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6 CONCLUSIONS

We studied the rotational properties of halo populations in the Milky Way Galaxy and Andromeda (M31). We modelled the gravitational potential, $\Phi$, and the density profile of the tracer population, $\rho$, as spherically symmetric power laws with indices $\gamma$ and $\epsilon$.
respectively. The shape of the velocity distribution is controlled by two parameters, namely $\beta$, which governs the velocity anisotropy, and $\eta$, which governs the rotation.

For our applications, we used the potential $\Phi \sim r^\gamma$ with $\gamma = 0.5$ as this is a good approximation to a NFW profile at large radii. Our tracer populations have a density profile $\rho \sim r^{-\alpha}$ with typically $\alpha = 3.5$. A maximum likelihood method is used to constrain the orbital parameters $\beta$ and $\eta$ for five different populations: (1) Milky way halo BHB stars; (2) Milky Way globular clusters; (3) Milky Way satellites; (4) M31 satellites and (5) M31 globular clusters. We summarize our conclusions as follows.

(1) From our constructed sample of halo BHB stars from SDSS, we find evidence for two different halo populations: a prograde-rotating, comparatively metal-rich component ([Fe/H] $> -2$) and a retrograde-rotating, comparatively metal-poor component ([Fe/H] $< -2$). The mean streaming motions are $\langle v_\phi \rangle = (21 \pm 11) (r/10 \text{kpc})^{-1/4} \text{km s}^{-1}$ and $\langle v_r \rangle = -35 (10) (r/10 \text{kpc})^{-1/4} \text{km s}^{-1}$ for the richer and poorer populations, respectively. A rough estimate suggests that these structures may have stellar masses of $M \sim 10^8 M_\odot$. We find evidence from the velocity dispersion profile that the metal-rich sample is associated with the accretion of a massive satellite. The line-of-sight velocity dispersion of the metal-rich sample has a kinematically cold component at $20 < r/\text{kpc} < 30$, which could be evidence for a shell-like structure caused by the accretion event. We find no such evidence to suggest the metal-poor sample is associated with an accretion event. We suggest that this population typifies the primordial stellar halo and the net retrograde rotation reflects an underestimate in our adopted local standard of rest circular velocity, which may be as high as $\sim 240 \text{km s}^{-1}$.

(2) The halo globular clusters of the Milky Way show evidence of net prograde rotation, $\langle v_\phi \rangle = (58 \pm 27) (r/10 \text{kpc})^{-1/4} \text{km s}^{-1}$, and have a mildly radial velocity distribution. Previous studies have found a mild net prograde rotation from an analysis of the line-of-sight velocities of the halo globular clusters (e.g. Frenk & White 1980). Our results are in agreement, but this deduction arises from the analysis of those 15 of the 41 halo globular clusters which have available proper motions. We note that the majority of our globular cluster sample have metallicities in the range $-2 < [\text{Fe/H}] < -1$ and are located within $10 < r/\text{kpc} < 20$. It is interesting that we also see net prograde rotation in the halo BHB stars in this distance and metallicity range. This suggests the relatively metal-rich BHBS and halo globular clusters may share a similar formation history.

(3) Line-of-sight velocities alone poorly constrain the orbital parameters of the Milky Way satellites. Using available proper motions for nine of the classical satellites, we find evidence for prograde rotation, $\langle v_\phi \rangle = (69 \pm 42) (r/10 \text{kpc})^{-1/4} \text{km s}^{-1}$, and a tangential anisotropy parameter $\beta = -1.5^{+0.9}_{-1.0}$. The orbits are preferentially polar. This leads to the detection of a more pronounced rotation when the normal vector of rotation is inclined by $|\theta| \approx 50^\circ$ to the normal of the disc. This hints that the satellites may be part of a rotationally supported disc (as postulated by a number of authors), but without more accurate proper motions this hypothesis cannot be confirmed.

(4) Application of these methods to the M31 satellites is potentially powerful, as the line-of-sight velocity has contributions from both the tangential and radial velocity components with respect to the M31 centre. The overall population shows hints of prograde rotation. We can divide the satellites into two groups. One possesses pronounced prograde rotation, $\langle v_\phi \rangle = (62 \pm 34) (r/10 \text{kpc})^{-1/4} \text{km s}^{-1}$, whilst the other shows no evidence for a rotating signal. Interestingly, the rotating group consists entirely of the dwarf spheroidal satellites. The correlation between satellite type and orbital orientation suggests these satellites may share a common origin.

(5) There is a rich data set on the M31 globular clusters which remains relatively unexploited. We examined the globular clusters with projected distance along the minor axis greater than 5 kpc. These outer globular clusters have prograde rotation which is more pronounced for the metal-rich ([Fe/H] $> -1$) subset. We find $\langle v_\phi \rangle = (94 \pm 35) (r/10 \text{kpc})^{-1/4} \text{km s}^{-1}$ for the metal-rich population and $\langle v_\phi \rangle = (53 \pm 34) (r/10 \text{kpc})^{-1/4} \text{km s}^{-1}$ for the metal-poor population. The strong rotation, especially in the metal-rich sample, suggests these globular clusters may belong to the M31 bulge system. However, confirmation awaits a more substantial kinematic sample extending further along the minor axis.

The Gaia satellite promises to provide proper motion data on all dwarf galaxies of the Milky Way and M31 and for thousands of halo stars. Wilkinson & Evans (1999) suggested that Gaia can constrain the proper motion of distant classical dwarfs in the Milky way, like Leo I, to within $\pm 15 \text{km s}^{-1}$ and nearer dwarfs like Ursa Minor to within $\pm 1 \text{km s}^{-1}$. Whilst Gaia will improve the proper motion measurements for the classical satellites, deeper complements to Gaia, such as the LSST, will be needed to achieve this level of accuracy for the ultrafaint satellites.

In anticipation of this future work, we close by considering Monte Carlo simulations of our DFs to estimate how well we can constrain rotation with these future astrometric surveys. We assume random errors on the tangential velocity component in the range $1 \text{km s}^{-1} \leq \sigma \leq 15 \text{km s}^{-1}$. Fig. 13 gives a rough estimate of how the accuracy depends on the number of satellites with proper motion measurements. For $N \approx 20$ satellites, we can constrain the mean streaming motion to $\sigma_\phi \approx 30 (r/10 \text{kpc})^{-1/4} \text{km s}^{-1}$. This evaluates to $\sigma_\phi \approx 10-20 \text{km s}^{-1}$ for satellites between $r = 50$ and $250 \text{kpc}$. The combination of more accurate proper motion measurements with radial velocities can potentially probe any apparent kinematic
dichotomy between the classical and ultrafaint satellites, and perhaps provide more robust evidence bearing on the disc of satellites.

Our analysis of the Milky Way stellar halo using BHB stars will be greatly improved by increasing the number of targets at larger radii. Coupled with more accurate radial velocity measurements, we will be able to map the kinematic structure of the stellar halo in greater detail and see if the apparent dual nature of the metal-rich and metal-poor components continues out to further reaches of the halo. LSST will hopefully play a vital role in finding these BHB targets.

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