

The spatial distribution of galactic satellites in the Λ cold dark matter cosmology

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ABSTRACT

We investigate the spatial distribution of galactic satellites in high-resolution simulations of structure formation in the Λ cold dark matter (Λ CDM) model: the Aquarius dark matter simulations of individual haloes and the Millennium-II simulation of a large cosmological volume. To relate the simulations to observations of the Milky Way we use two alternative models to populate dark haloes with ‘visible’ galaxies: a semi-analytic model of galaxy formation and an abundance matching technique. We find that the radial density profile of massive satellites roughly follows that of the dark matter halo (unlike the distribution of dark matter subhaloes). Furthermore, our two galaxy formation models give results consistent with the observed profile of the 11 classical satellites of the Milky Way. Our simulations predict that larger, fainter samples of satellites should still retain this profile at least up to samples of 100 satellites. The angular distribution of the classical satellites of the Milky Way is known to be highly anisotropic. Depending on the exact measure of flattening, 5–10 per cent of satellite systems in our simulations are as flat as the Milky Way’s and this fraction does not change when we correct for possible obscuration of satellites by the Galactic disc. A moderate flattening of satellite systems is a general property of Λ CDM, best understood as the consequence of preferential accretion along filaments of the cosmic web. Accretion of a single rich group of satellites can enhance the flattening due to such anisotropic accretion. We verify that a typical Milky Way-mass cold dark matter halo does not acquire its 11 most massive satellites from a small number of rich groups. Single-group accretion becomes more likely for less massive satellites. Our model predictions should be testable with forthcoming studies of satellite systems in other galaxies and surveys of fainter satellites in the Milky Way.

Key words: methods: numerical – Galaxy: structure – Galaxy: formation – dark matter.

1 INTRODUCTION

The satellites of the Milky Way (MW) offer a number of critical tests of the current cosmological paradigm, the Λ cold dark matter (Λ CDM) model. Their abundance and internal structure are sensitive to the nature of the dark matter (DM) and thus to the high-frequency end of the linear power spectrum of density fluctuations. Their spatial distribution is sensitive to the gravitational evolution of DM on galactic and supergalactic scales.

High-resolution simulations of the formation of galactic cold dark matter (CDM) haloes have revealed that a large number of substructures survive to the present day, accounting for about 10 per cent of the total halo mass (Diemand, Kuhlen & Madau 2007; Springel et al. 2008, and references therein). Since only about two dozen

satellites are known to orbit in the halo of the MW, this property is frequently deemed to pose a ‘satellite problem’ for CDM-based cosmologies. In fact, it was shown about a decade ago that basic processes that are unavoidable during galaxy formation, such as supernova feedback and early Hydrogen reionization, readily explain why a visible satellite galaxy can form only in a tiny fraction of the surviving subhaloes (Bullock, Kravtsov & Weinberg 2000; Benson et al. 2002; Somerville 2002). This result has been confirmed repeatedly in recent years using semi-analytic models (Cooper et al. 2010; Li, De Lucia & Helmi 2010; Macciò et al. 2010; Font et al. 2011; Guo et al. 2011a), cosmological gasdynamical simulations (Okamoto et al. 2010; Wadepuhl & Springel 2011; Parry et al. 2012) and simplified semi-empirical models (Kravtsov, Gnedin & Klypin 2004; Koposov et al. 2009; Muñoz et al. 2009; Busha et al. 2010).

A different kind of theoretical challenge is posed by the spatial distribution of the 11 classical satellites of the MW. Lynden-Bell

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(1976), Kunkel (1979) and Lynden-Bell (1982) noted that these satellites lie very close to a great circle on the sky that is approximately perpendicular to the Galactic plane. Kroupa, Theis & Boily (2005) deemed such a highly flattened structure to be extremely unlikely in a CDM cosmology but, using N -body simulations of halo formation in the Λ CDM model, Kang et al. (2005), Libeskind et al. (2005), Zentner et al. (2005) and Libeskind et al. (2009) showed explicitly that this presumption is incorrect. Such flattened satellite distributions were dubbed ‘great pancakes’ by Libeskind et al. (2005) who ascribed them to highly anisotropic accretion of protosubhaloes along the filaments of the cosmic web. Correlated accretion along filaments was also identified as the cause for the polar alignment of satellite discs found by Deason et al. (2011) in 20 per cent of satellite systems (with more than 10 bright members each) in the ‘GIMIC’ N -body/gasdynamic simulations (Crain et al. 2009). Although all of these studies found that flattening of satellite systems is common in Λ CDM, they also found that the high degree of flattening in the MW system is atypical. Although satellites appear to be distributed anisotropically around the MW and Andromeda (Metz et al. 2009), studies of large samples of late-type galaxies suggest that the average distribution is closer to isotropic (Bailin et al. 2008; Yegorova, Pizzella & Salucci 2011; Guo et al. 2012; Nierenberg et al. 2012). The satellites of early types are more likely to be aligned with the major axis of the galaxy light (Brainerd 2005; Agustsson & Brainerd 2010; Nierenberg et al. 2012).

Li & Helmi (2008) showed that the flattening effects of anisotropic accretion are greatly enhanced in cases where infalling DM subhaloes belong to a ‘group’ sharing similar infall times and orbital angular momentum orientations (the members of such groups do not have to be bound in a single DM halo before infall). In a MW-mass system, they found that samples of ~ 10 subhaloes drawn from one or two such groups readily produced configurations as flat as that of the classical MW satellites. Extrapolating this result, they suggested that the highly correlated infall of a rich group of satellites was a possible explanation for the abnormal degree of flattening seen in the MW. However, they could not quantify the probability of this explanation since they did not calculate the likelihood of all the 11 *brightest* satellites being members of only one or two such groups.

An important limitation of the simulations that have been analysed so far to study the spatial distribution of satellites is their relatively low resolution. Low resolution can give rise to excessive tidal disruption and to the artificial merging of some subhaloes (Kazantzidis et al. 2011), potentially obscuring the true spatial distribution. In this paper, we use the suite of six simulations of individual Galactic haloes from the Aquarius Project, which are amongst the highest resolution CDM simulations carried out to date (Springel et al. 2008), as well as a sample of similar haloes from the Millennium-II simulation (Boylan-Kolchin et al. 2009). Millennium II has lower resolution than Aquarius but follows halo formation in a cosmological volume (a cube of side $100 h^{-1}$ Mpc, where h denotes the Hubble constant in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$). With the Aquarius simulations, we are able to study satellites down to very small masses in six galactic haloes and with the Millennium II we are able to study the massive satellites of a large sample of galactic haloes. Since the Aquarius haloes are zoom resimulations of regions in the Millennium-II volume, we are also able to study the effects of numerical resolution.

We rank satellites in our simulations by stellar mass using two different techniques: semi-analytic modelling and a simple assignment of the brightest satellites to the most massive protosubhaloes. As we show, the two approaches pick out similar subsets of sub-

haloes as satellite hosts. With these samples, we revisit the radial distribution of satellites and the great pancake and, for the first time, we investigate how these properties depend on the number of satellites considered (in samples ranked by stellar mass). This allows us to make predictions for forthcoming surveys such as Pan-STARRS (Kaiser et al. 2010), which may discover a large population of very faint satellites in the MW and M31, and the ongoing PANDAS survey of M31 (McConnachie et al. 2009; Martin et al. 2009). We also extend the work of Li & Helmi (2008) by using Aquarius to investigate the multiplicity function of groups of massive satellites.

The paper is organized as follows. In Section 2, we discuss the suite of simulations and galaxy formation models that we use. In Section 3, we investigate the radial distribution of satellites, the prevalence of great pancakes and groups of massive satellites. Our conclusions and discussion are presented in Section 4.

2 SATELLITE IDENTIFICATION

We begin by providing a brief introduction to the Aquarius and Millennium-II simulations and then describe the two alternative techniques we have employed to identify satellites in them.

2.1 Aquarius and Millennium II

The Aquarius Project (Springel et al. 2008) consists of a suite of very high resolution N -body simulations of six DM haloes of mass similar to that expected for the halo of the MW. The simulations assume the Λ CDM cosmology, with parameters consistent with the *Wilkinson Microwave Anisotropy Probe* (*WMAP*) 1 data (Spergel et al. 2003): matter density parameter, $\Omega_M = 0.25$; cosmological constant term, $\Omega_\Lambda = 0.75$; power spectrum normalization, $\sigma_8 = 0.9$; spectral slope, $n_s = 1$; and Hubble parameter, $h = 0.73$. These values are inconsistent with the *WMAP* 7 data at about the 2σ level, but this discrepancy is of no consequence for the analysis of this paper (see Wang et al. 2012).

The six Aquarius haloes are labelled ‘Aq-A’ through ‘Aq-F’. Each was resimulated at different resolution in order to assess numerical convergence. A suffix 1 to 5 identifies the resolution level, with level 1 denoting the highest resolution. In this study, we analyse primarily the level 2 simulations. For the level 2 simulations, the particle mass is $m_p \simeq 1 \times 10^4 h^{-1} M_\odot$ and the softening length is $\epsilon = 48 h^{-1} \text{ pc}$. At $z = 0$, the six haloes have a ‘virial’ mass, $M_{200} \sim 1\text{--}2 \times 10^{12} h^{-1} M_\odot$, where M_{200} is the mass contained within r_{200} , the radius of a sphere of mean density 200 times the critical density for closure. The circular velocity curves of the haloes peak at $V_{\text{max}} = 220 \pm 40 \text{ km s}^{-1}$. Although the Aquarius haloes have similar final masses, they have varied formation histories (Wang et al. 2011). For further details of the Aquarius Project, we refer the reader to Springel et al. (2008) and Navarro et al. (2010).

At every snapshot in the simulations we find non-linear structures using the friends-of-friends (FOF) algorithm of Davis et al. (1985), with a linking length of 0.2 times the mean interparticle separation and 32 particles as the minimum number of particles per group. We also identify bound substructures within each FOF halo using the SUBFIND algorithm of Springel et al. (2005). Merger trees for subhaloes are constructed as described in Springel et al. (2008).

The Millennium-II run (MII) is a cosmological simulation in which 2160^3 particles were followed in a cubic box of side length $L_{\text{box}} = 100 \text{ Mpc } h^{-1}$. This volume is 125 times smaller than that of the Millennium simulation (Springel et al. 2005), and the mass resolution is correspondingly 125 times better: each particle has mass $6.88 \times 10^6 h^{-1} M_\odot$. The cosmological model is the same as

that assumed for the Aquarius Project. For further details, we refer the reader to Boylan-Kolchin et al. (2009).

The Aquarius haloes are resimulations of regions selected from a low-resolution version of the M_{RII} with identical large-scale density perturbations and phases in their initial conditions. We can therefore find the counterparts of each Aquarius halo in the M_{RII} and carry out resolution tests (see Boylan-Kolchin et al. 2009). The resolution of the M_{RII} is similar to that of the simulations analysed by Kang et al. (2005) and Zentner et al. (2005), but it is a factor of ~ 30 worse than the simulation by Libeskind et al. (2005) and a factor of ~ 20 better than that by Libeskind et al. (2009).

2.2 Galaxy formation models

There are two techniques for modelling satellite galaxies in detail using simulations: direct hydrodynamic simulations and semi-analytic modelling applied to a high-resolution N -body simulation of the DM. The two techniques are similar, differing primarily in the simplified, spherically symmetric treatment of gasdynamics in the semi-analytic method. In this study, we are interested in very faint satellites. Even the highest resolution gasdynamic simulations of satellites performed to date (Okamoto et al. 2010; Wadepuhl & Springel 2011) can resolve only the dozen or so brightest galaxies of a MW system and so they are not suitable for our purposes. Semi-analytic models, on the other hand, are restricted only by the resolution of the associated N -body simulation so we resort instead to the semi-analytic models applied to the Aquarius simulations by Cooper et al. (2010) and to the M_{RII} by Guo et al. (2011a). We refer the reader to these papers for details of the implementation. An added advantage of the semi-analytic models is that, unlike the direct gasdynamic simulations, these models are known to agree with a whole range of other properties of the galaxy population at various epochs.

In practice, despite the complexity of the many physical processes they incorporate, both gasdynamic and semi-analytic simulations predict an approximately monotonic relation between the stellar mass of a galaxy and the total mass of the halo in which it forms. As we are only interested in the stellar mass rank of satellites, it is instructive to consider a much simpler model for satellites in which the stellar mass (hence luminosity) of each satellite is assumed to be proportional to the highest value of the maximum of the circular velocity curve (V_{\max}) attained by the halo in which the satellite forms throughout its entire history. We denote this by V_{peak} ; it corresponds roughly to the value of V_{\max} just prior to the halo being accreted into the main halo and becoming a subhalo. We refer to this as the ‘ V_{peak} model’. By comparing our semi-analytic results with this simpler but fundamentally similar model, we can check if our conclusions depend on the details of the semi-analytic treatment, which introduces a scatter in the relationship between stellar mass and (maximum) halo mass.

The correspondence between V_{peak} and M_{star} , the stellar mass of the semi-analytic model of Cooper et al. (2010), is illustrated in Fig. 1. The expected monotonic relation is apparent. However, there is considerable scatter in the relation for subhaloes with $V_{\text{peak}} \lesssim 25 \text{ km s}^{-1}$. At higher masses, in the range of the 11 classical satellites, the relation flattens and the scatter is greatly reduced. In this regime, over 90 per cent of the satellites with the highest V_{peak} values also have the highest M_{star} according to the semi-analytic model. Fig. 1 shows that our simple V_{peak} model will give a ranking of subhaloes by stellar mass very similar to that of the semi-analytic model, in most cases.

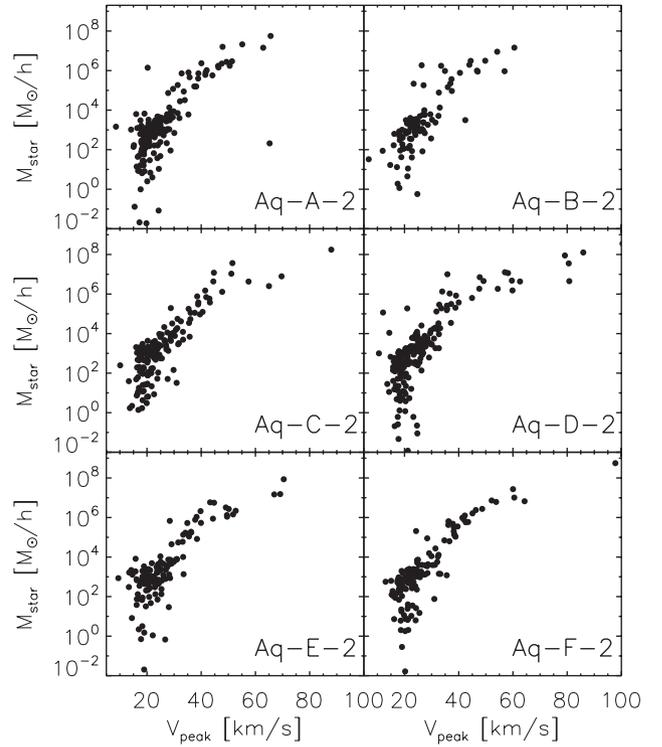


Figure 1. The relationship between the stellar mass assigned by the Cooper et al. (2010) semi-analytic model to subhaloes in the six Aquarius simulations and the maximum value of the rotation curve attained by each subhalo over its entire past history. (Satellites with unresolved DM haloes are excluded.) The tight correlation for the most massive satellites motivates a simple V_{peak} model for ranking satellites by stellar mass.

The internal structure of haloes that are close to the resolution limit of an N -body simulation is, of course, poorly modelled. This can lead to the artificial disruption of these haloes when they are accreted into larger haloes. The baryonic properties of their associated galaxies can still be followed in semi-analytic models even after the subhaloes fall below the resolution of the simulation, but as their orbits cannot be tracked within the N -body simulation their spatial distribution is uncertain and model dependent. The resolution of the Aquarius simulations is so high that we need not worry about galaxies with unresolved haloes (see discussion of this point in Font et al. 2011). However, at the lower resolution of the M_{RII}, galaxies in unresolved haloes do need to be taken into account, as discussed by Guo et al. (2011a). This conclusion is supported by our investigation of the radial distribution of satellites in M_{RII} in the following section. We demonstrate that convergence with Aquarius is only possible if we include galaxies without resolved subhaloes in the Guo et al. model. In addition, because the circular velocity scale corresponding to the V_{peak} of the most massive satellites ($30\text{--}60 \text{ km s}^{-1}$) is close to the resolution limit of M_{RII}, we can only make reliable comparisons between the semi-analytic and the V_{peak} models in the Aquarius simulations, and not in the M_{RII}.

In Fig. 2, we compare the projected positions of the top 11, 30, 60 and 100 satellites ranked by stellar mass in Aq-A-2 according to the semi-analytic model (diamonds) and the V_{peak} method (full circles). As we can see in the top-left panel, 10 out of the top 11 satellites are the same in both models, an overlap ratio, $f = 10/11 = 0.91$. As we consider smaller and more numerous satellites, f decreases, but even for the top 100 satellites, f is still as high as 70 per cent.

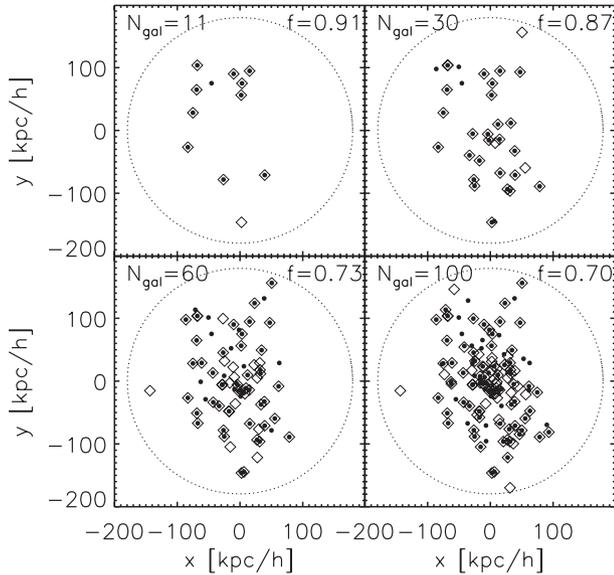


Figure 2. The projected positions of satellites identified using the Cooper et al. (2010) semi-analytic model (diamonds) and the V_{peak} method (filled circles) in the Aq-A2 halo. From top left to bottom right, positions are shown for the top 11, 30, 60 and 100 satellites ranked by stellar mass in each model. The overlap ratio between the two samples is given in the legend. It decreases from $f = 0.91$ for the top 11 to $f = 0.7$ for the top 100 satellites.

In Fig. 3, we compare the overlap fractions between the top N_{gal} satellites ranked according to the stellar mass assigned by the Cooper et al. (2010) model and various simplified but plausible models for identifying satellites with subhaloes, including our standard V_{peak} model (black line with error bars). The overlap fraction for the V_{peak} model tends to a constant, $f \simeq 0.75$, for $N_{\text{gal}} \gtrsim 60$. The green line corresponds to the case in which satellites are identified with the most massive subhaloes at the present day (Stoehr et al. 2002). Clearly, this method fails to place satellites in similar subhaloes to those picked out by our two standard models. The reason for this is simply that the present mass of a subhalo is significantly affected by tidal stripping and thus is only weakly correlated with the mass of the halo prior to accretion, during which time most of the satellite stars form.

Identifying satellites instead with subhaloes ranked by the maximum mass they ever attain (blue line) gives a better match to the standard models since this mass is better correlated with the satellite’s stellar mass or luminosity. Even in this case, though, the overlap falls to just over 60 per cent for large satellite populations. The red line shows what happens if we identify satellites according to the value of V_{peak} attained prior to $z = 6$, roughly the redshift of reionization. This model gives similar results to our standard V_{peak} model, except for the most massive satellites, reflecting, in part, the fact that reionization plays a relatively minor role in setting the stellar mass of these galaxies (see e.g. Okamoto et al. 2010; Font et al. 2011). We conclude that our choice of V_{peak} is the most appropriate of these alternatives and in most of the remainder of this paper we focus on comparisons between satellites ranked by this property and by the stellar mass in our semi-analytic models.

3 RESULTS

In this section, we consider the spatial distribution of satellite galaxies predicted in both our semi-analytic and V_{peak} models and compare them with data for satellites in the MW.

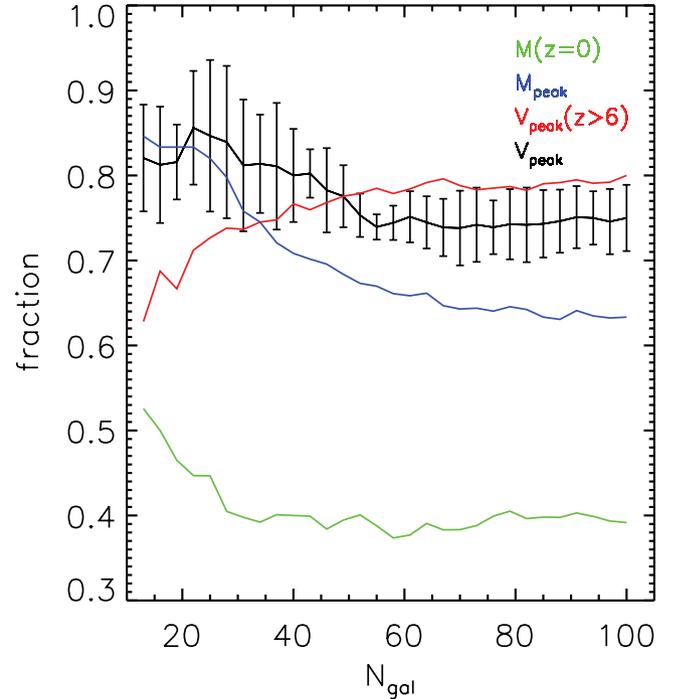


Figure 3. The fraction of satellites ranked according to different criteria that overlap with the top N_{gal} satellites ranked according to the stellar mass assigned to them by the Cooper et al. (2010) semi-analytic model. The data correspond to the mean value for all six Aquarius haloes. The black line shows the overlap with our standard V_{peak} model and the 1σ error bar obtained from the six Aquarius simulations. The green line shows the result of ranking satellites according to their present mass and the blue line according to the maximum mass ever attained by the halo in which they reside today. The red line is similar to the V_{peak} model, except that in this case V_{peak} is defined as the maximum value attained by V_{max} before $z = 6$, approximately the redshift of reionization.

3.1 Radial profiles

The radial distribution of the 11 classical satellites of the MW¹ is shown by the filled circles in Fig. 4. The Galactocentric distance used here is taken from Mateo (1998). It is close to the radial distribution of the DM in the Aquarius haloes, shown in the figure by the black dotted line, a similarity already noted by Kang et al. (2005), Libeskind et al. (2005) and Font et al. (2011). To compare the data to our models, we select the top 11 satellites in each model that lie within a distance of 250 kpc from the centre of the halo, roughly the distance of Leo I, the most distant of the observed MW 11.

Results for the semi-analytic, V_{peak} , $V_{\text{peak}}(z > 6)$ and $M_{\text{max}}(z = 0)$ models are shown by the green, black, blue and red solid lines, respectively. All, except the last, are roughly consistent with the data within the large uncertainties due to small number of statistics (see also Cooper et al. 2010; Font et al. 2011). By contrast, identifying satellites with the most massive present-day subhaloes (red line) leads to a much more extended distribution which, as first noted by Libeskind et al. (2005), closely follows the radial profile of the entire halo population. This is consistent with the finding by

¹ The ‘classical’ satellites of the MW are usually defined as the top 11 ranked by V-band luminosity, whereas throughout this paper we select the top 11 ranked by stellar mass. In our model, these definitions almost always select the same galaxies.

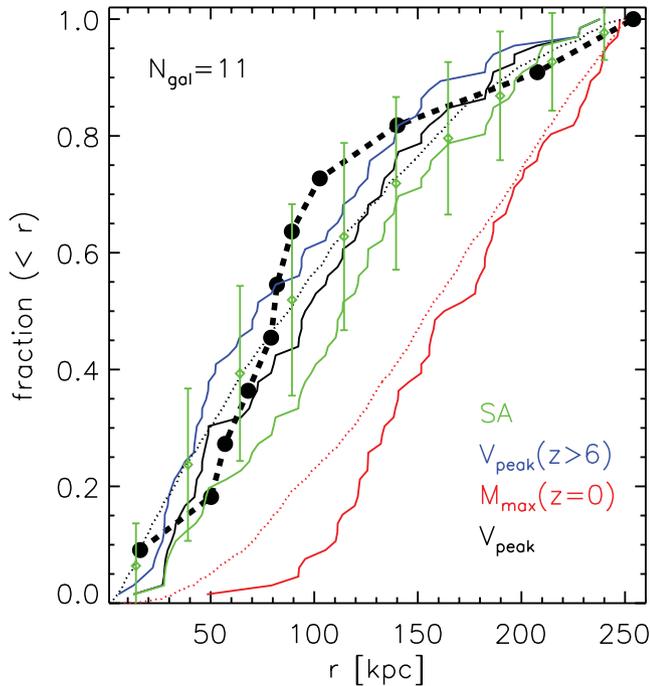


Figure 4. The radial profiles of the top 11 satellites in different models. Results have been averaged over the six Aquarius haloes. The profile of the 11 classical satellites of the MW is shown by the filled circles joined with a thick dashed black curve. The radial profile of the DM is shown by the black dotted curve and the radial profile of all resolved subhaloes in the six Aquarius haloes by the red dotted curve. The green, blue, red and black lines show the distribution of satellites in the Aquarius simulations, identified using different models, as indicated in the legend. The green diamonds with error bars correspond to satellites in the semi-analytic model applied to the M_RII, including satellites without resolved DM haloes.

Springel et al. (2008) that the radial profile of subhaloes depends very weakly on subhalo mass. The other, more realistic, models place bright satellites in subhaloes whose radial profiles are strongly biased relative to that of the subhalo population as a whole and which happen to lie close to the DM radial profile. We also show results for MW galaxies from the semi-analytic model applied to the M_RII, taking care to include satellites which survive even though their DM haloes have been tidally stripped. The distribution is close to the observational data. However, had we not included satellites without resolved DM haloes, the profile would lie close to that of all subhaloes (red dotted).

The model lines in Fig. 4 are smoother than the MW data because we averaged the distributions of the 11 top-ranked satellites from each of the six Aquarius haloes. There is, in fact, considerable halo to halo scatter, as may be seen in Fig. 5, which shows the radial profiles of the 11 brightest satellites predicted by the semi-analytic model in each halo. Five of these lie very close to the MW data but in Aq-A, the radius enclosing half of the satellites is over twice as large as in the other five Aquarius haloes.

Fig. 5 also highlights the importance of high-resolution simulations for this kind of study. Since the Aquarius haloes were selected from the M_RII, we can identify their counterparts in that simulation, as described by Boylan-Kolchin et al. (2010). The radial profiles of the top 11 satellites in these counterparts, as identified in the V_{peak} model, are shown by the dotted lines in the figure, with colours corresponding to those of the Aquarius haloes. Satellites in the M_RII counterparts are clearly much more extended than the Aquarius

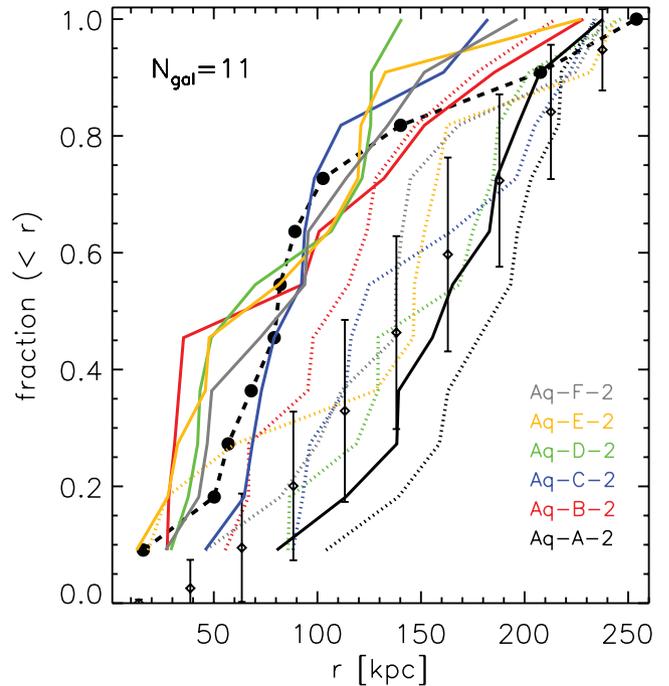


Figure 5. The radial profile of the 11 brightest satellites according to the V_{peak} model in each of the six Aquarius haloes (solid lines) and in their counterparts in the M_RII (dotted lines). The diamonds and large error bars correspond to the average profile and 1σ dispersion of the top 11 satellites identified by the V_{peak} model in 1686 M_RII haloes of mass $1 \times 10^{12} < M_{200} < 2 \times 10^{12} M_{\odot}$. The profile of the 11 classical MW satellites is shown by the black circles joined with a dashed black curve.

subhaloes. This is typical of the satellite distributions in MW-mass haloes in the M_RII, as illustrated by the diamonds with error bars, obtained by averaging the distributions of the 11 brightest satellites in the 1686 M_RII haloes of mass $1 \times 10^{12} \leq M_{200} \leq 2 \times 10^{12}$. The M_RII has about 1000 times lower resolution than the level 2 Aquarius simulations. As a result, subhalo orbits are not followed as accurately and their disruption time-scale is artificially reduced.

The semi-analytic model of Guo et al. (2011a) allows galaxies to survive after their host subhalo falls below the resolution limit. A position is assigned to these galaxies by tracking the most bound particle of the host subhalo from the time it was last resolved. This position is unlikely to be a very accurate estimate of the true orbit of the satellite; for example, Guo et al. make an analytic correction to this single-particle orbit when calculating the tidal disruption of the satellite, as the orbits of individual particles do not decay through dynamical friction in an N -body simulation. Nevertheless, when we include satellites with unresolved haloes in our top 11 sample, as was done in Fig. 4 (but *not* in Fig. 5), and use their single-particle position estimates, the M_RII radial profiles for the Aquarius galaxies are in reasonable agreement with their higher resolution counterparts.

As we expect that larger and more complete samples of fainter satellites will soon be available for the MW and other galaxies, it is interesting to know how the radial profiles of satellites are predicted to vary with the luminosity cut of the sample. This is a question that we can address with the Aquarius simulations and we do this in Fig. 6, where we show the radial profiles of the top 11, 30, 60 and 100 galaxies predicted in the semi-analytic (solid curves) and V_{peak} (dotted curves) models. The profiles depend only weakly on the size of the sample within the mass range we can examine: they are all

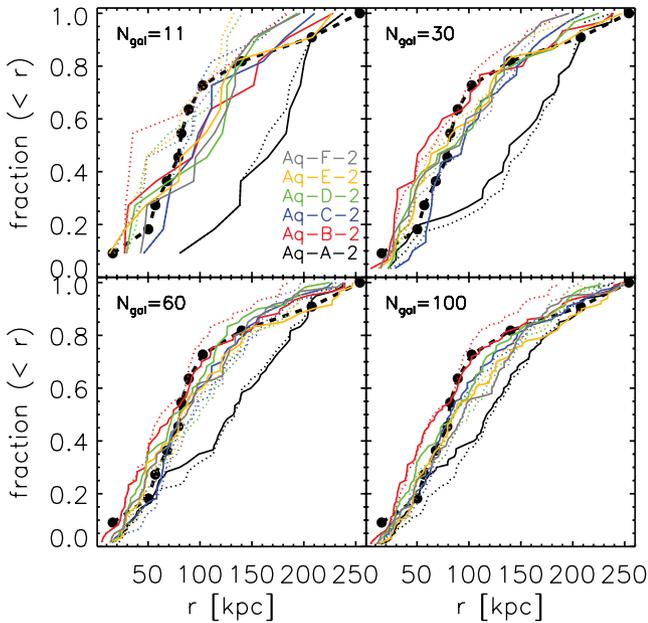


Figure 6. The cumulative radial profiles of the top N_{gal} satellites in each of the Aquarius haloes in the semi-analytic (solid lines) and V_{peak} (dotted lines) models. The profile of the 11 classical satellites of the MW is shown in all panels by the solid dots joined by a thick dashed black curve.

similar to that of the 11 classical satellites of the MW. The exception is Aq-A whose profiles become increasingly less discrepant with the other five Aquarius cases as the satellite sample size increases (although it is still the least concentrated even when 100 satellites are considered). By most other measures Aq-A is representative of haloes of the same mass (Boylan-Kolchin et al. 2010), suggesting that the top 11 satellites may often exhibit ‘unusual’ configurations in otherwise ‘typical’ haloes.

3.2 The angular distribution of satellites and the great pancake

As we have seen in the preceding section, the semi-analytic and V_{peak} models reproduce the observed radial profile of the 11 classical satellites of the MW. In this subsection, we investigate if they also reproduce the highly flattened configuration seen in the MW, first noted by Lynden-Bell (1976) and investigated more recently by Kroupa et al. (2005), Libeskind et al. (2005), Kang et al. (2005), Libeskind et al. (2009) and Deason et al. (2011). We use similar techniques to those introduced by Libeskind et al. (2005) and Kang et al. (2005) to describe the flattening of the satellite population, namely, the overall shape of its distribution and its thickness in the flattest dimension.

3.2.1 The axis ratios of satellite systems

To determine the shape of a satellite system we calculate the moment of inertia tensor of its members (weighting each of them equally) and derive the principal axes of the distribution. The eigenvalues of the diagonalized inertia tensor are proportional to the root-mean-square (rms) deviation of the x , y and z coordinates of the system. Denoting the major, intermediate and minor axes by a , b and c , respectively ($a > b > c$), the flattening of the system may be quantified by the axial ratios c/a and b/a .

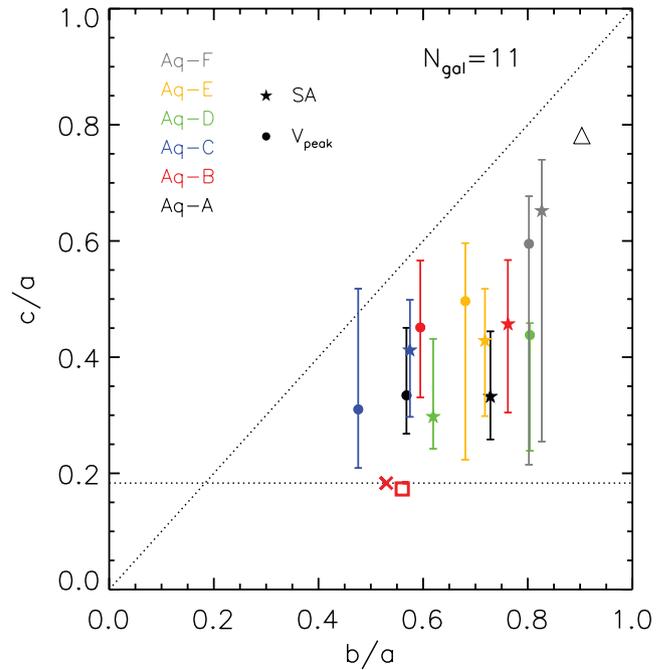


Figure 7. The axis ratios describing the shape of satellite systems in the Aquarius simulations and in the MW. c/a is the minor to major axis ratio and b/a the intermediate to major axis ratio. Results for the top 11 satellites in the semi-analytic and V_{peak} models are shown by asterisks and filled circles, respectively, with error bars spanning the range obtained for a large sample of satellites taking into account systematic effects introduced by the zone of avoidance (see the text for details). The axis ratios for the 11 classical satellites of the MW are shown with a red cross with the value of c/a highlighted by the horizontal dotted line. The average axis ratios of the six Aquarius DM halo (within r_{200}) are shown as the large open triangle towards the top-right corner. The red square shows the effect of including Canes Venatici in the observational sample.

The axial ratios of the system consisting of the 11 classical satellites of the MW are indicated by a red cross in Figs 7 and 8, with the value of $c/a = 0.18$ highlighted by the horizontal dotted line. This is slightly lower than the value obtained by Libeskind et al. (2005) who had an error in their computer code (Libeskind, private communication). The faintest of the 11 classical satellites are Draco and Ursa Minor ($M_V = -8.8$), but Canes Venatici is just 0.2 mag fainter than this (McConnachie 2012). We have checked that including Canes Venatici has virtually no effect in the estimated axis ratios of the system, as shown by the red square in Fig. 7.

The corrected value of c/a for the MW’s classical satellite appears quite extreme. However, with a sample of only 11 objects, it is not immediately obvious that a value even as low as $c/a = 0.18$ is significant. To assess the significance of this result, we follow Libeskind et al. (2005) and create a large number of artificial systems of 11 satellites in which the radial distances of the members are the same as the distances of the real satellites, but the latitude and longitude are assigned at random on the surface of a sphere. Isocontours of axial ratios for a set of 10 000 such isotropic systems, corresponding to number fractions of 30, 60 and 90 per cent, are shown as red curves in Fig. 8. We find that only 98 of these samples result in values of c/a smaller than 0.18. Thus, we conclude that the distribution of the 11 classical satellites of the MW is highly anisotropic, with only a 1 per cent probability that such a low value of c/a would result from a statistical fluctuation of an intrinsically isotropic system.

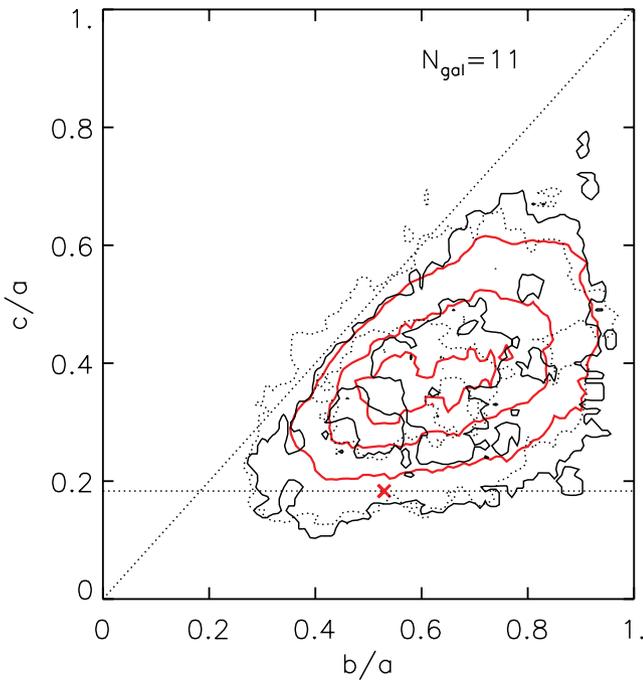


Figure 8. The distribution of shape parameters for systems of 11 satellites. The black lines show results for systems around 1686 MW like haloes in the MR11 and the dotted lines indicate the results after correcting for missing satellites in the Galactic plane as described in the text. The red lines show results for 10 000 randomly selected systems with the same radial distribution as the observed satellites of the MW, but with a uniform distribution in solid angle. The three contour levels correspond to fractions of 30, 60 and 90 per cent. The axis ratios of the 11 classical satellites of the MW are indicated by the red cross, with the value of c/a highlighted by the horizontal dotted line.

Applying the same procedure to the simulations we obtain the axis ratios for systems consisting of the top 11 satellites, ranked by stellar mass, that lie within 250 kpc of the centre in our two models. The results are shown in Fig. 7 for the six Aquarius haloes, using asterisks for the semi-analytic model and circles for the V_{peak} model. We also plot the average axis ratios of the six Aquarius haloes as a whole (within r_{200}) as a large triangle. The axis ratios of the 11 classical satellites of the MW are plotted as a red cross. Three conclusions emerge from this figure. First, as noted earlier by Libeskind et al. (2005) and Kang et al. (2005), massive satellite systems can be much flatter than the halo as a whole. Secondly, the two methods for ranking galaxies by stellar mass give very similar results. Thirdly, the satellite systems in the simulations appear generally less flattened than the 11 classical MW satellites.

Although it is often assumed that the 11 classical satellites represent a complete sample of bright satellites in the central regions of the MW, it is, of course, possible that bright satellites might remain undetected in the zone of avoidance as a result of both large extinction and confusion by foreground stars. Assuming that satellites are intrinsically uniformly distributed in $(1 - \sin|b|)$, where b denotes Galactic latitude, Willman et al. (2004) estimated that the known population of dwarf satellites could be 33 per cent incomplete because of obscuration. However, Whiting et al. (2007) argued that, at most, there are one or two dwarfs still undiscovered near the Galactic plane.

To assess the possible effects of obscuration, we assume a geometry for the Galactic disc in our simulations and exclude satellites in the corresponding zone of avoidance. The ‘great pancake’ in the

MW lies perpendicular to the Galactic disc. We therefore imagine that each of our Aquarius haloes has a ‘Galactic plane’ whose normal is parallel to the major axis of its satellite system. We then calculate the latitude of each satellite relative to this plane. If the latitude is less than a critical value, $\pm\theta_{\text{crit}}$, we regard this satellite as undetected and exclude it from our sample of 11, replacing it by the next in the list. (For a 33 per cent occulted sky fraction, $\theta_{\text{crit}} = 9.5^\circ$.) We repeat this process iteratively 2000 times, each time recalculating the shape of the current satellite system and the position of the obscuring ‘Galactic plane’. In 2000 cases, satellites were hidden behind the model Galactic plane and replaced, on average, with 2.6 new satellites.

The results of this procedure, for $\theta_{\text{crit}} = 9.5^\circ$, are reflected in Fig. 7 as error bars spanning the range of c/a , with the uncorrected sample shown as a filled symbol. It is striking that the inferred shape of the satellite system is extremely sensitive to the inclusion or exclusion of only one or two members. Allowing for sample incompleteness improves the comparison between models and data notably, with several of the models now coming close to the data.

To improve our statistics, we also analysed satellite systems in the MR11. As discussed earlier, the V_{peak} model is strongly affected by the relatively low resolution of the MR11, but not so the semi-analytic model, provided satellites with DM haloes below the resolution limit are included in the analysis. As before, we consider all DM haloes with virial mass $1 \times 10^{12} \leq M_{200} \leq 2 \times 10^{12}$ that have at least 11 satellites within 250 kpc. This provides a sample of 1686 MW haloes. The axis ratios of the brightest 11 satellites in each of the systems are shown as the black contours in Fig. 8, where levels correspond to number fractions of 30, 60 and 90 per cent. We find only 101 satellite systems with an axis ratio c/a smaller than the observed value of 0.18, giving a probability of finding a configuration flatter than that in the MW of only $101/1686 = 6$ per cent.

Just as for the Aquarius sample, we make a correction for the possible omission of satellites near the Galactic disc. For each halo, we assume a Galactic plane perpendicular to the minor axis of the satellite distribution, draw 2000 random samples (replacing lost satellites and iterating) and obtain the mean values of the axis ratios. As the dotted contour in Fig. 8 shows, the probability of finding a system in the simulations as flat or flatter than that of the MW is not sensitive to our corrections for obscuration by the Galactic disc (under the assumption that the minor axes of the satellite system and the disc are perpendicular).

The high mass resolution of the Aquarius simulations allows us to investigate how the flattening of the satellite system varies as increasingly faint satellites are included in the sample and thus to make predictions for the larger samples that may become available in the future as surveys such as Pan-STARRS1 and LSST discover new, fainter satellites in the MW. The axial ratios for systems of $N_{\text{gal}} = 11, 22, 44$ and 66 satellites are shown in the four panels of Fig. 9. The minimum and maximum values amongst the six Aquarius haloes, after correcting for the effects of the zone of avoidance, as discussed above, are indicated by the error bars. Fig. 9 shows that, as the size of the satellite sample increases, the distribution becomes increasingly less flattened, in agreement with the results of Kang et al. (2005). When the sample size reaches 66, the shape of the satellite configuration is very close to that of halo DM, indicated by a large triangle in each panel. This prediction from our simulations should be readily testable with potentially forthcoming samples of new faint satellites, provided their selection functions are well understood.

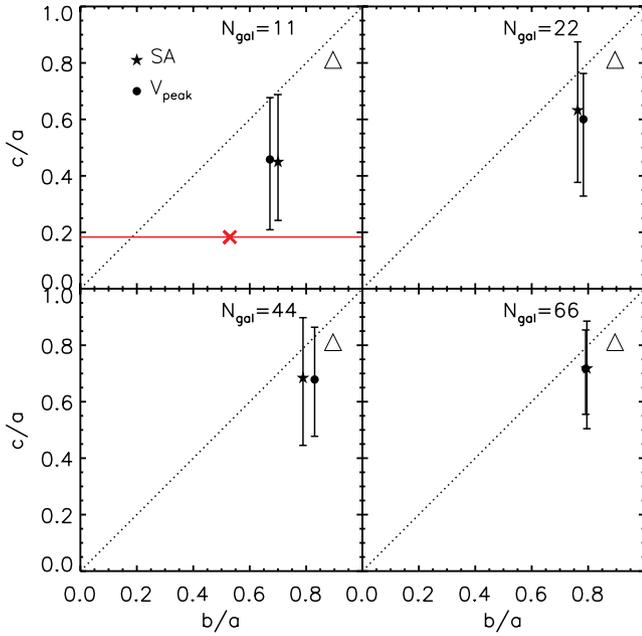


Figure 9. Shape parameters for systems consisting of the top N_{gal} satellites according to our two models of satellite galaxy formation. The symbols (asterisks for the semi-analytic model and filled circles for the V_{peak} model) give the directly measured mean values, averaged over the six Aquarius haloes. The error bars span the minimum and maximum values amongst the six haloes after correction for satellites missing due to obscuration in the Galactic plane. The four panels show results for $N_{\text{gal}} = 11, 22, 44$ and 66 . In the top-left panel, the values for the top 11 satellites of the MW ranked by luminosity are indicated by a red cross, with the value of c/a highlighted by a red horizontal solid line. The triangle near the top-right corner of each panel shows the mean axis ratios of the entire DM distribution in the six Aquarius haloes.

3.2.2 The thickness of the satellite ‘disc’

An alternative method to estimate the flattening of the ‘Great pancake’ is to measure the thickness of the slab defined by the pancake. Following Kroupa et al. (2005) and Kang et al. (2005), we find the best-fitting plane to a given satellite sample by minimizing the rms of the height of each satellite relative to the plane. The thickness of the slab is taken to be the rms height about the best-fitting plane and the ratio of the thickness to the radial extent of the system, $R_{\text{cut}} = 250$ kpc, is used to characterize its flattening.

The flattening of the satellite disc in each of the six Aquarius haloes is shown in Fig. 10. The four panels correspond to systems with different numbers of members, N_{gal} . Results for our two different satellite galaxy formation models are indicated by the filled symbols. The open symbols show results for 20 000 artificial samples with the same radial distribution as the corresponding Aquarius sample but with random angular positions on the sky. In some cases (e.g. Aq-A in all panels, Aq-D in the $N_{\text{gal}} = 11$ panel and Aq-C in the $N_{\text{gal}} = 22$ panel), the simulated satellite systems are significantly anisotropic but in others, the open symbols lie close to the filled symbols, indicating that these systems show no significant flattening according to this test. In the top-left panel, we compare the model results with the measurement for the 11 classical satellites of the MW, whose thickness (indicated by the red line) is 0.074. This population is clearly flatter than most of the simulations, although the satellite systems in Aq-C and Aq-D come close. The remaining panels in Fig. 10 show that, as was the case for the axial ratios,

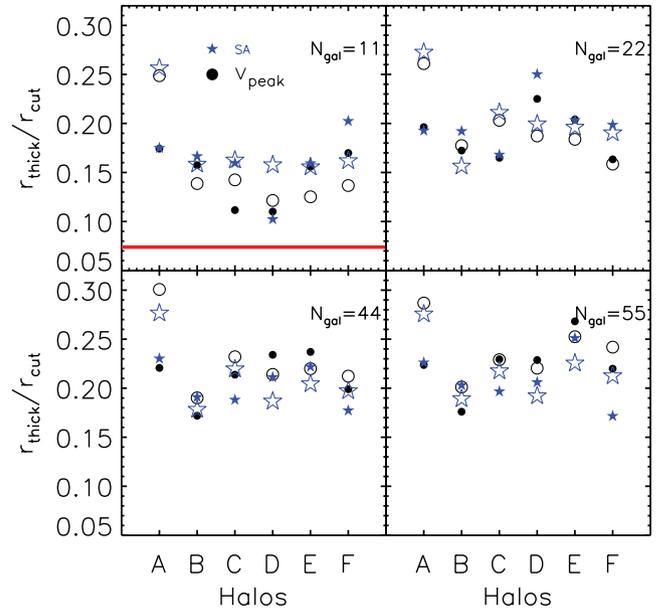


Figure 10. The flattening (defined as the ratio of the rms height of the satellites relative to the best-fitting plane divided by the radial extent of the system) of the satellite distribution in the six Aquarius haloes. Different panels correspond to samples containing the top N_{gal} satellites according to our two models of satellite formation, which are illustrated by the filled symbols, as indicated in the legend. The open symbols show the average of 20 000 artificial samples each with the same radial distribution as the corresponding Aquarius sample but with random angular positions on the sky. In the $N_{\text{gal}} = 11$ panel the flattening of the 11 brightest satellites of the MW, 0.074, is indicated by a red solid line.

systems containing more and more satellites become progressively less flattened.

We also estimated the thickness of satellite systems in the 1686 MW like haloes found in the MR11 as described in Section 3.2.1, which provides better statistics than the Aquarius haloes. The histogram of flattening values is shown in Fig. 11. The value measured for the 11 classical satellites of the MW, 0.074, is indicated by the vertical dashed line. This degree of flattening is highly significant: of 10 000 artificial isotropic samples of 11 satellites having the same radial distribution as the observed satellites (red histogram), only 107 are flatter than the MW system. This corresponds to a probability of only 1.07 per cent. In the MR11 a total of 219 cases have flatter satellite systems than the MW, corresponding to a probability of 13 per cent. When the effects of the Galactic disc are taken into account, the distribution of flattenings is not significantly affected (dotted histogram in Fig. 11).

3.3 The multiplicity of accreted groups

As we have seen, the distribution of satellites in the MW is significantly anisotropic. Libeskind et al. (2005) ascribed this striking property to the accretion of satellites along a few filaments of the cosmic web. However, in agreement with previous studies, we have shown that, although flattened satellite systems are common, the MW’s satellites are even more flattened than the expectation for haloes of similar mass. Li & Helmi (2008) noted that the natural flattening induced by this anisotropic infall is strongest when considering samples of galaxies accreted in ‘groups’, defined by common infall conditions (time, direction and orientation of orbital angular momentum). Considering all DM subhaloes regardless of

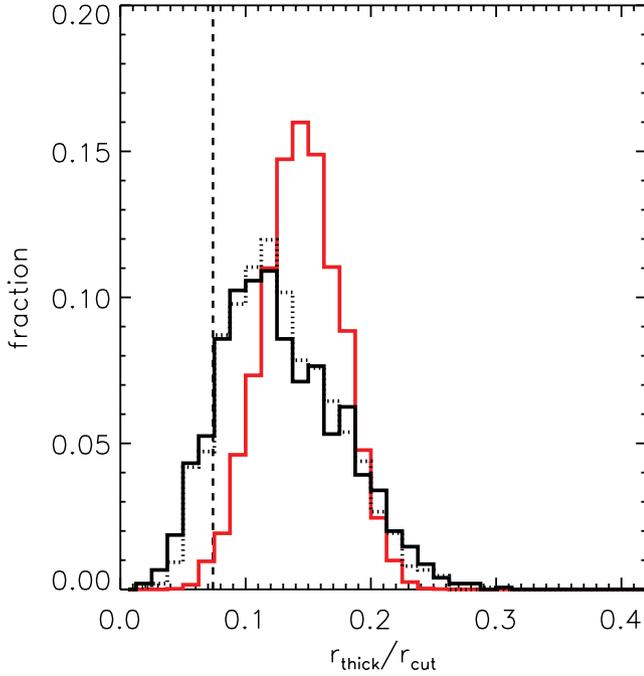


Figure 11. The distribution of flattenings (obtained from the *rms* height of satellites relative to the best-fitting plane) for satellite systems. The solid black line shows results for the 1686 haloes in the MII with $1 \times 10^{12} \leq M_{200} \leq 2 \times 10^{12}$ that have at least 11 satellites within 250 kpc. The red histogram corresponds to 10 000 samples with the same radial distribution as the 11 classical satellites of the MW and a random distribution of angles on the sphere. The dotted histogram shows results for the MII corrected for the possible loss of satellites near the Galactic disc taken from 2000 realizations. The flattening of the 11 classical satellites of the MW, 0.074, is shown as a dashed vertical line.

their mass, they found that samples of 11 subhaloes drawn from only one such infalling ‘group’ have a configuration as flat as the classical MW satellite distribution in 73 per cent of cases. This probability falls to only 20 per cent if only 5/11 satellites are drawn from a single group. However, since Li & Helmi studied only one high-resolution halo, they were unable to quantify how likely it is that the *most massive* 11 satellites of the MW fell in just one or two groups and so to test whether or not this process is a probable explanation for their unusually flat configuration.

In order to explore the effect studied by Li & Helmi (2008) in our six ‘typical’ MW haloes, we identify satellites at the final time in the simulation and trace them back to the FOF group to which they belonged before they were accreted. If two or more satellites were part of the same group at one or more subsequent simulation snapshots, we regard them as correlated (Li & Helmi 2008 did not require their correlated subhaloes to be members of the same FOF group, only to share similar infall times, directions and orbital angular momentum orientations; in practice the two definitions are likely to have similar results). In Fig. 12 we plot, for each Aquarius halo, the number of groups in which a given number of satellites were brought into the main halo (counting only satellites surviving to redshift zero). As before, we identify satellites using both our semi-analytic and V_{peak} models (indicated by diamonds and crosses, respectively) and we consider samples of $N_{\text{gal}} = 11$ (red symbols) and $N_{\text{gal}} = 60$ (black symbols) satellites. The fractions of correlated haloes relative to the total number of satellites ($f_{c,SA}$ for the semi-analytic model and $f_{c,VP}$ for the V_{peak} model) are given in the legend.

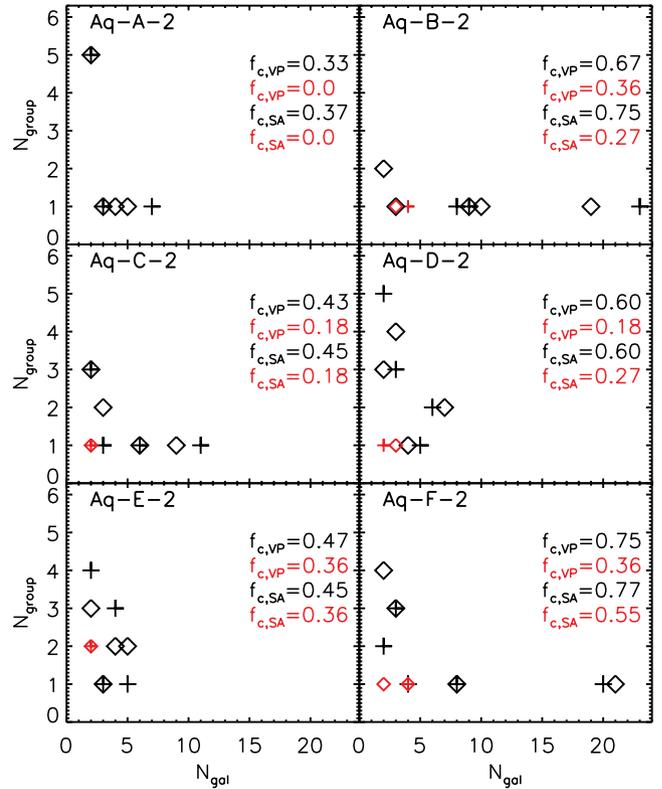


Figure 12. Histogram of multiple accretion satellite events in the six Aquarius haloes. Satellites identified by the semi-analytic model are shown as diamonds, while those identified by the V_{peak} model are shown as crosses. In both cases, red symbols correspond to the top 11 satellites and black symbols to the top 60. The fractions of correlated haloes relative to the total number of satellites, $f_{c,SA}(N)$ for the semi-analytic model and $f_{c,VP}(N)$ for the V_{peak} model, where N is the number of satellites in the system, are given in the legend.

Focusing first on the top 11 satellites in each model (red symbols), we can see that, except in the semi-analytic model for halo F, fewer than half of these satellites are members of groups according to our definition; that is, more than half are accreted singly into the main halo. This suggests that the probability of the top 11 satellites falling into the halo as members of only two or three groups is low; the moderate flattenings of the Aquarius satellite systems represent the typical outcome of anisotropic accretion, and are not enhanced by closer orbital associations between particular satellites. Testing whether or not the extreme flattening of the MW’s system can be explained by the rare occurrence of a handful of ‘rich’ or ‘top heavy’ accretion events, as proposed by Li & Helmi (2008), will require a much larger suite of simulations comparable to Aquarius.

The prevalence of strongly correlated accretion increases as we consider larger satellite samples. For example, in haloes B and F more than 15 of the top 60 satellites were part of a single group before accretion, as may be seen in Fig. 12. The increase in $f_{c,SA}$ and $f_{c,VP}$ with the size of the satellite sample is illustrated in Fig. 13 and is seen in both our methods for ranking satellites. For systems of only 10 satellites, the correlated fraction is ~ 10 –50 per cent, but this rises to ~ 30 –80 per cent for systems of 100 satellites. Our findings reinforce the conclusion of Lovell et al. (2011) that a more complete census of satellite motions in the MW and M31 will reveal a significant fraction with common orbital planes.

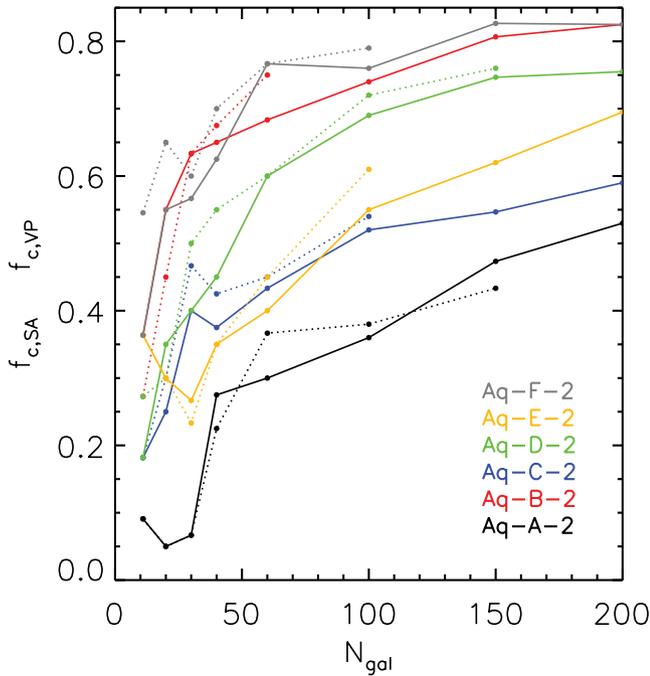


Figure 13. The fraction of the top N_{gal} satellites which are accreted into the main halo in a group with at least one partner, as a function of N_{gal} . The dotted lines show results for satellites in the semi-analytic model ($f_{c,\text{SA}}$), the solid lines for satellites in the V_{peak} model ($f_{c,\text{VP}}$).

4 CONCLUSION AND DISCUSSION

The spatial distribution of satellites in the MW and other galaxies reflects both the nature of the DM and the processes of galaxy formation. In this paper, we have used high mass resolution cosmological simulations of structure formation in the Λ CDM model: the Aquarius resimulations of galactic scale DM haloes and the Millennium-II simulation (MII) of a cubic volume $100 h^{-1}$ Mpc on a side, with about 2000 haloes of mass comparable to the MW’s halo. We have further employed two models of galaxy formation to trace satellites in the simulation: the semi-analytic models of Cooper et al. (2010) and Guo et al. (2011a) for Aquarius and MII, respectively, and a less sophisticated model in which galaxy stellar mass is assumed to be proportional to V_{peak} , the highest circular velocity attained by the halo throughout its life. Our two methods place 10 of the most massive 11 satellites in the same Aquarius haloes.

The combination of high-resolution simulations and robust galaxy formation models allows us to identify satellites in a reliable way. We find that good mass resolution is essential to obtain an accurate estimate of the radial distribution of satellites. Indeed, even at the resolution of the MII, $m_p = 6.9 \times 10^6 h^{-1} M_{\odot}$, many genuine substructures are artificially destroyed, as may be seen in Fig. 5. In this case, the V_{peak} method for assigning stellar mass to satellites, as well as all previous cosmological simulations which have poorer resolution (e.g. Kang et al. 2005; Libeskind et al. 2005), would give inaccurate results. By contrast, our semi-analytic model, which continues to track satellites even after they have lost their haloes does give a faithful prediction of the theoretical expectations in the Λ CDM model. In the case of the Aquarius simulations, the resolution is good enough that galaxies with unresolved haloes are unimportant (Font et al. 2011) and we can compare our semi-analytic results with the V_{peak} method. The results from the two ranking methods agree well.

Our main results concerning the satellite radial distribution are: (i) there is substantial halo-to-halo scatter in the radial distribution of satellites in the Aquarius simulations, but in all cases the massive satellites have a similar radial density profile to that of the DM; (ii) both the semi-analytic and V_{peak} models give results in good agreement with the measured radial distribution of the 11 classical satellites of the MW; (iii) the radial density profile of larger satellite samples, going down to lower masses, is similar to that of the 11 most massive, at least up to samples of 100 satellites. This prediction may be tested by future surveys such as Pan-STARRS.

Several studies have found that the radial distribution of subhaloes is more concentrated in hydrodynamical simulations than in DM only simulations (Macciò et al. 2006; Libeskind et al. 2010; Schewtschenko & Macciò 2011). However, these differences are limited to the inner regions of the host halo, and such effects are unlikely to change the typical anisotropy of the satellite system, which (when defined using the unnormalized inertia tensor) is more sensitive to satellites at larger radii. Also, the formation of satellite galaxies is known to be strongly influenced by the local ionizing background (e.g. Busha et al. 2010; Font et al. 2011). The relative importance of local and background sources of reionization may alter the satellite luminosity function and radial distribution (Ocvirk & Aubert 2011), although further work is required to better understand these effects.

We also investigated the angular distribution of satellites. This is interesting because the MW’s 11 brightest satellites show a very anisotropic distribution, the ‘Great pancake’ of Libeskind et al. (2005). We characterized the angular distribution by measuring both the axial ratios of the satellite system and the thickness of the slab in which the satellites are concentrated. We verified that the peculiar distribution seen in the MW is highly significant: only 1 per cent of isotropic samples with the same radial distribution are flatter than the MW’s system. In the 1686 haloes in the MII which have a mass plausibly similar to that of the MW we find systems flatter than that of the classical satellites with probabilities of 6 and 13 per cent according to the axial ratio and slab thickness tests, respectively. These probabilities are slightly lower than that found by Libeskind et al. (2005), who used a slightly incorrect value for the flattening of the MW satellites. Our probabilities are also lower than those found by Kang et al. (2005), a discrepancy that is readily understood as a consequence of the poor mass resolution of the simulations used by these authors. The MW system thus appears to be in the tail of the flattening distribution expected for massive satellites in the Λ CDM model. The presence of a satellite as massive as the Large Magellanic Cloud (Boylan-Kolchin et al. 2010; Busha et al. 2011; Guo et al. 2011b; Liu et al. 2011) and the polar alignment of the system (Deason et al. 2011) seem to be comparably rare, but still consistent with the predicted distributions.

Finally, we investigated the extent to which satellites are accreted in groups. This is interesting for several reasons, including the possibility that the great pancake might be explained by multiple accretion in 2–3 groups (Li & Helmi 2008). Our simulations confirm that this is a rare occurrence in Λ CDM. On average, only 30 per cent of the top 11 satellites in the Aquarius simulations share a FOF group with another top 11 satellites before infall; the rest come into the main halo without any companions of comparable mass. However, multiple accretion becomes increasingly important for larger, fainter samples of satellites. For example, in samples of the 60 most massive satellites in two of the Aquarius haloes (Aq-B and Aq-F), we find that as many as 20 come into the main halo in a single group and as many as 11 in the other simulated

haloes. This interesting property may potentially have observational consequences (e.g. Sales et al. 2011).

Libeskind et al. (2005) proposed that filamentary accretion is responsible for the flattening of MW-like satellite populations. Lovell et al. (2011) subsequently showed that the subhaloes of the Aquarius simulations have strongly correlated orbital angular momenta as the result of anisotropic accretion. Recently, however, Pawlowski et al. (2012) re-analysed the angular momentum orientations of subhaloes in Aquarius (as presented in Lovell et al. 2011) and concluded that anisotropic accretion is unimportant for producing flattened satellite systems, in direct contradiction with the results of Libeskind et al. (2005, 2011) and Lovell et al. (2011). They required that the MW flattening should be reproduced in the mean, rather than being merely consistent with the expected distribution. As the MW is in the ~ 10 per cent tail of the distribution predicted by Λ CDM (as our study and others have shown), they reject a CDM model in favour of tidal galaxy formation, which they claim readily produces highly correlated discs of satellites. We believe that the explanation offered by Libeskind et al. (2005) remains the most appropriate. A single randomly chosen system such as the MW is extremely unlikely perfectly to represent the mean value of every measurable property. A larger sample of satellites around other galaxies will test the tidal formation hypothesis of Pawlowski et al. (2012) in which highly flattened configurations are easily achieved and should therefore be the norm. If, on the other hand, the CDM model is a realistic description of nature, then the average satellite configurations should be only moderately flattened, as illustrated in Figs 7 and 8. The origin of the relative rarity of highly flattened systems like that of the MW remains an open question deserving further consideration.

Our simulations are useful not only to test our models against data for the classical satellites of the MW, as we have done here, but also to make predictions for future surveys that will quantify the spatial distribution of larger and fainter satellite samples, both in the MW and in other galaxies. For a sample of MW satellites complete to very faint magnitudes, we have shown that the luminosity function (Font et al. 2011), radial distribution and system shape should vary less from halo to halo than is the case for the most massive 11. Measuring these three highly characteristic properties of the satellite system test both the Λ CDM cosmology and models of galaxy formation in novel, interesting ways.

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