Cosmic ménage à trois: the origin of satellite galaxies on extreme orbits

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ABSTRACT

We examine the orbits of satellite galaxies identified in a suite of N-body/gasdynamical simulations of the formation of L∗ galaxies in a Lambda cold dark matter universe. The numerical resolution of the simulations allows us to track in detail the orbits of the ∼ 10 brightest satellites around each primary. Most satellites follow conventional orbits; after turning around, they accrete into their host halo and settle on orbits whose apocentric radii are steadily eroded by dynamical friction. As a result, satellites associated with the primary are typically found within its virial radius, rvir, and have velocities consistent with a Gaussian distribution with mild radial anisotropy. However, a number of outliers are also present. We find that a surprising number (about one-third) of satellites identified at z = 0 are on unorthodox orbits, with apocentres that exceed their turnaround radii. These include a number of objects with extreme velocities and apocentric radii at times exceeding ∼3.5r_{vir} (or, e.g. ≳1 Mpc when scaled to the Milky Way). This population of satellites on extreme orbits consists typically of the faint member of a satellite pair whose kinship is severed by the tidal field of the primary during first approach. Under the right circumstances, the heavier member of the pair remains bound to the primary, whilst the lighter companion is ejected on to a highly energetic orbit. Since the concurrent accretion of multiple satellite systems is a defining feature of hierarchical models of galaxy formation, a fairly robust prediction of this scenario is that at least some of these extreme objects should be present in the Local Group. We speculate that this three-body ejection mechanism may be the origin of (i) some of the newly discovered high-speed satellites around M31 (such as Andromeda XIV); (ii) some of the distant fast-receding Local Group members, such as Leo I and (iii) the oddly isolated dwarf spheroidals Cetus and Tucana in the outskirts of the Local Group. Our results suggest that care must be exercised when using the orbits of the most weakly bound satellites to place constraints on the total mass of the Local Group.

Key words: galaxies: evolution – galaxies: formation – galaxies: haloes – galaxies: kinematics and dynamics.

1 INTRODUCTION

The study of Local Group satellite galaxies has been revolutionized by digital imaging surveys of large areas of the sky. More than a dozen new satellites have been discovered in the past couple of years (Zucker et al. 2004; Willman et al. 2005; Belokurov et al. 2006; Martin et al. 2006; Zucker et al. 2006; Belokurov et al. 2007; Irwin et al. 2007; Majewski et al. 2007), due in large part to the completion of the Sloan Digital Sky Survey (York et al. 2000; Strauss et al. 2002) and to concerted campaigns designed to image in detail the Andromeda galaxy and its immediate surroundings (Ibata et al. 2001; Ferguson et al. 2002; Reitzel & Guhathakurta 2002; McConnachie et al. 2003; Rich et al. 2004; Chapman et al. 2006; Gilbert et al. 2006; Guhathakurta et al. 2006; Ibata et al., submitted). The newly discovered satellites have extended the faint end of the galaxy luminosity function down to roughly ∼10^1 L⊙, and are likely to provide important constraints regarding the mechanisms responsible for ‘lighting up’ the baryons in low-mass haloes. These, in turn, will serve to validate (or falsify) the various theoretical models attempting to reconcile the wealth of ‘substructure’ predicted in cold dark matter (CDM) haloes with the scarcity of luminous satellites in the Local Group (see e.g. Klypin et al. 1999; Bullock, Kravtsov & Weinberg 2000; Benson, Frenk & Sharples 2002; Stoehr et al. 2002; Kazantzidis et al. 2004; Kravtsov, Gnedin & Klypin 2004; Penarrubia, McConnachie & Navarro 2007).

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At the same time, once velocities and distances are secured for the newly discovered satellites, dynamical studies of the total mass and spatial extent of the Local Group will gain new impetus. These studies have a long history (Little & Tremaine 1987; Zaritsky et al. 1989; Kochanek 1996; Wilkinson & Evans 1999; Evans & Wilkinson 2000; Battaglia et al. 2005), but their results have traditionally been regarded as tentative rather than conclusive, particularly because of the small number of objects involved, as well as the sensitivity of the results to the inclusion (or omission) of one or two objects with large velocities and/or distances (Zaritsky et al. 1989; Kochanek 1996; Sakamoto, Chiba & Beers 2003). An enlarged satellite sample will likely make the conclusions of satellite dynamical studies more compelling and robust.

To this end, most theoretical work typically assumes that satellites are in equilibrium, and use crafty techniques to overcome the limitations of small-N statistics when applying Jeans’ equations to estimate masses (see e.g. Little & Tremaine 1987; Wilkinson & Evans 1999; Evans & Wilkinson 2000). With increased sample size, however, follow enhanced opportunities to discover satellites on unlikely orbits; that is, dynamical ‘outliers’ that may challenge the expectations of simple-minded models of satellite formation and evolution. It is important to clarify the origin of such systems, given their disproportionate weight in mass estimates.

One issue to consider is that the assumption of equilibrium must break down when considering outliers in phase space. This is because the finite age of the Universe places an upper limit to the orbital period of satellites observed in the Local Group; high-speed satellites have typically large apocentres and long orbital periods, implying that they cannot be dynamically well mixed and casting doubts on the applicability of jeans’ theorem-inspired analysis tools.

To make progress, one possibility is to explore variants of the standard secondary infalling model (Gunn & Gott 1972; Gott 1975; Gunn 1977; Fillmore & Goldreich 1984), where satellites are assumed to recede initially with the universal expansion, before turning around and collapsing on to the primary due to its gravitational pull. This is the approach adopted by Zaritsky & White (1994) in order to interpret statistically the kinematics of observed satellite samples without assuming well-mixed orbits and taking into account the proper timing and phase of the accretion process.

In the secondary infalling accretion sequence, satellites initially farther away accrete later, after turning around from larger turnaround radii. The turnaround radius grows with time, at a rate that depends on the mass of the primary and its environment, as well as on the cosmological model. Three distinct regions surround a system formed by spherical secondary infall (see e.g. Bertschinger 1985; Navarro & White 1993): (i) an outer region beyond the current turnaround radius where satellites are still expanding away, (ii) an intermediate region containing satellites that are approaching the primary for the first time and (iii) an inner, ‘virialized’ region containing all satellites that have turned around at earlier times and are still orbiting around the primary. To a good approximation, the latter region is delineated roughly by the conventional virial radius of a system.\footnote{We define the virial radius, $r_{\text{vir}}$, of a system as the radius of a sphere of mean density $\Delta_{\text{vir}}$ times the critical density for closure. This definition defines implicitly the virial mass, $M_{\text{vir}}$, as that enclosed within $r_{\text{vir}}$, and the virial velocity, $V_{\text{vir}}$, as the circular velocity measured at $r_{\text{vir}}$. We compute $\Delta_{\text{vir}} (z)$ using $\Delta_{\text{vir}} (z) = 18\pi^2 [1 - 6\ln(1 + z) + z]$, where $\Delta_{0} = \Omega_{0}/\Omega_{m} = 1$ and $\Omega_{0} = \Omega_{\Lambda} + \Omega_{m}$ (Bryan & Norman 1998), and is $\sim 100$ at $z \approx 0$.}

$r_{\text{vir}}$; the turnaround radius is of the order of $r_{\text{ta}} \sim 3r_{\text{vir}}$ (see e.g. White et al. 1993).

We note a few consequences of this model. (i) Satellites outside the virial radius are on their first approach to the system and thus have not yet been inside $r_{\text{vir}}$. (ii) Satellites inside the virial radius have apocentric radii that typically do not exceed $r_{\text{vir}}$. (iii) The farther the turnaround radius the longer it takes for a satellite to turn around and accrete and the higher its orbital energy. (iv) Satellites with extreme velocities will, in general, be those completing their first orbit around the primary. Velocities will be maximal near the centre, where satellites may reach speeds as high as $\sim 3V_{\text{vir}}$. (v) Since all satellites associated with the primary are bound (otherwise they would not have turned around and collapsed under the gravitational pull of the primary), the velocity of the highest speed satellite may be used to estimate a lower limit to the escape velocity at its location and, thus, a lower bound to the total mass of the system.

Hierarchical galaxy formation models, such as the current $\Lambda$CDM paradigm, suggest further complexity in this picture. First, although numerical simulations show that the sequence of expansion, turnaround and accretion of satellites described above is more or less preserved in hierarchical models, the evolution is far from spherically symmetric (Navarro, Frenk & White 1994; Gill et al. 1998; Jing & Suto 2002; Bailin & Steinmetz 2005; Knebe & Theuerkauf 2006). Much of the mass (as well as many of the satellites) is accreted through filaments of matter embedded within sheets of matter formation (see e.g. Navarro, Abadi & Steinmetz 2004). The anisotropic collapse pattern on to a primary implies that the turnaround ‘surface’ won’t be spherical and that the virial radius may not contain all satellites that have completed at least one orbit around the primary (see e.g. Balogh, Navarro & Morris 2000; Diemand, Kuhlen & Madau 2007).

More importantly for the purposes of this paper, in hierarchical models galaxy systems are assembled by collecting smaller systems which themselves, in turn, were assembled out of smaller units. This implies that satellites will in general not be accreted in isolation, but frequently as part of larger structures containing multiple systems. This allows for complex many-body interactions to take place during approach to the primary that may result in substantial modification to the orbits of accreted satellites.

We address this issue in this contribution using $N$-body/gasdynamical simulations of galaxy formation in the current $\Lambda$CDM paradigm. We introduce briefly the simulations in Section 2, and analyse and discuss them in Section 3. We speculate on possible applications to the Local Group satellite population in Section 4 and conclude with a brief summary in Section 5.

2 THE NUMERICAL SIMULATIONS

We identify satellite galaxies in a suite of eight simulations of the formation of $L_*$ galaxies in the $\Lambda$CDM scenario. This series has been presented by Abadi, Navarro & Steinmetz (2006), and follow the same numerical scheme originally introduced by Steinmetz & Navarro (2002). The ‘primary’ galaxies in these simulations have been analysed in detail in several recent papers, which the interested reader may wish to consult for details (Abadi et al. 2003a,b; Meza et al. 2003; Navarro et al. 2004; Meza et al. 2005). We give a brief outline below for completeness.

Each simulation follows the evolution of a small region of the universe chosen so as to encompass the mass of an $L_*$ galaxy system. This region is chosen from a large periodic box and resimulated at higher resolution preserving the tidal fields from the whole box.
The simulation includes the gravitational effects of dark matter, gas and stars, and follows the hydrodynamical evolution of the gaseous component using the smoothed particle hydrodynamics technique (Steinmetz 1996). We adopt the following cosmological parameters for the ΛCDM scenario: $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\sigma_8 = 0.9$, $\Omega_m = 0.7$, $\Omega_{\Lambda} = 0.255$, $\Omega_b = 0.045$, with no tilt in the primordial power spectrum.

All resimulations start at redshift $z_{\text{init}} = 50$, have force resolution of the order of 1 kpc, and the mass resolution is chosen so that each galaxy is represented on average, at $z = 0$, with $\sim 50,000$ dark matter/gas particles. Gas is turned into stars at rates consistent with the empirical Schmidt-like law of Kennicutt (1998). Because of this, star formation proceeds efficiently only in high-density regions at the centre of dark haloes, and the stellar components of primary and satellite galaxies are strongly segregated spatially from the dark matter.

Each resimulation follows a single $\sim L_*$ galaxy in detail, and resolves as well a number of smaller, self-bound systems of stars, gas, and dark matter we shall call generically ‘satellites’. We shall hereafter refer to the main galaxy indistinctly as ‘primary’ or ‘host’. The resolved satellites span a range of luminosities, down to about 6 or 7 mag fainter than the primary. Each primary has on average $\sim 10$ satellites within the virial radius.

Fig. 1 illustrates the $z = 0$ spatial configuration of star particles in one of the simulations of our series. Only star particles are shown here, and are coloured according to their age: stars younger than $\simeq 1$ Gyr are shown in blue; those older than $\simeq 10$ Gyr in red. The large box is centred on the primary and is $2 r_{\text{vir}}$ (632 kpc) on a side. The ‘primary’ is situated at the centre of the box and contains most of the stars. Indeed, although not immediately apparent in this rendition, more than 85 per cent of all stars are within $\sim 20$ kpc from the centre. Outside that radius most of the stars are old and belong to the stellar halo, except for a plume of younger stars stripped from a satellite that has recently merged with the primary. Satellites ‘associated’ with the primary (see Section 3.1 for a definition) are indicated with small boxes. Note that a few of them lie well beyond the virial radius of the primary.

A preliminary analysis of the properties of the simulated satellite population and its relation to the stellar halo and the primary galaxy has been presented in Abadi et al. (2006) and Sales et al. (submitted), where the interested reader may find further details.

3 RESULTS AND DISCUSSION

3.1 Satellites on conventional orbits

The evolution of satellites in our simulations follows roughly the various stages anticipated by our discussion of the secondary infalling model; after initially receding with the universal expansion, satellites turn around and are accreted into the primary. Satellites
massive enough to be well resolved in our simulations form stars actively before accretion and, by the time they cross the virial radius of the primary, much of their baryonic component is in a tightly bound collection of stars at the centre of their own dark matter haloes.

The stellar component of a satellite is thus quite resilient to the effect of tides and can survive as a self-bound entity for several orbits. This is illustrated by the solid lines in Fig. 2, which show, for one of our simulations, the evolution of the distance to the primary of two satellites that turn around and are accreted into the primary at different times. As expected from the secondary infalling model, satellites that are initially farther away turn around later; do so from larger radii; and are on more energetic orbits. After accretion (defined as the time when a satellite crosses the virial radius of the primary), their orbital energy and eccentricity are eroded by dynamical friction, and these two satellites do not leave the virial radius of the primary, which is shown by a dotted line. The light member of the pair, on the other hand, is ejected from the system as a result of a three-body interaction between the pair and the primary during first approach. One of the ejected satellites shown here is the ‘escaping’ satellite identified in Fig. 3; the other is the most distant ‘associated’ satellite in that figure. The latter is still moving towards apocentre at \( z = 0 \), which we estimate to be as far as \( \sim 3.5 r_{\text{vir}} \).

in this figure) are confined within \( r_{\text{vir}} \), and that their velocity distribution is reasonably symmetric and consistent with a Gaussian (Sales et al., submitted). The most recently accreted satellites tend to have higher-than-average speed at all radii, as shown by the ‘crossed’ circles, which identify all satellites accreted within the last 3 Gyr. Crosses (without circles) in this figure correspond to satellites that have not yet been accreted into the primary. These show a clear infalling pattern outside \( r_{\text{vir}} \), where the mean infalling velocity decreases with radius and approaches zero at the current turnaround radius, located at about 3 \( r_{\text{vir}} \). All of these properties agree well with the expectations of the secondary infalling model discussed above.

3.2 Three-body interactions and satellites on unorthodox orbits

Closer examination, however, shows a few surprises. To begin with, a number of ‘associated’ satellites are found outside \( r_{\text{vir}} \). As reported in previous work (see e.g. Balogh, Navarro & Morris 2000; Moore et al. 2004; Gill, Knebe & Gibson 2005; Diemand, Kuhlen & Madau 2007), these are a minority (~15% per cent in our simulation

\( \phi, \theta \)
Satellites on extreme orbits

Figure 4. Distribution of the ratio between the apocentric radius of satellites (measured at \( z = 0 \)) and their turnaround radius, defined as the maximum distance to the primary before accretion. Note the presence of two groups. Satellites on ‘conventional’ orbits have \( r_{apo}/r_{tu} < 1 \), the rest have been catapulted into high-energy orbits by three-body interactions during first approach. The satellite marked with a rightward arrow is the ‘escaping’ satellite identified by a dot-centred circle in Fig. 3; this system has nominally infinite \( r_{apo} \). The dashed histogram highlights the population of low-mass satellites; that is, those with stellar masses at accretion time not exceeding 2.6 per cent of the primary’s final \( M_{\odot} \). The satellite marked with an arrow is a formal ‘escaper’ for which \( r_{apo} \) cannot be computed.

These effects may account for some of the associated satellites found outside \( r_{vir} \) at \( z = 0 \), but cannot explain why \( \sim 33 \) per cent of all associated satellites are today on orbits whose apocentres exceed their turnaround radius. This is illustrated in Fig. 4, where we show a histogram of the ratio between apocentric radius (measured at \( z = 0 \); \( r_{apo} \)) and turnaround radius (\( r_{tu} \)). The histogram highlights the presence of two distinct populations: satellites on ‘conventional’ orbits with \( r_{apo}/r_{tu} < 1 \), and satellites on orbital paths that lead them well beyond their original turnaround radius.

Intriguingly, a small but significant fraction (\( \sim 6 \) per cent) of satellites have extremely large apocentric radius, exceeding their turnaround radius by 50 per cent or more. These systems have clearly been affected by some mechanism that propelled them on to orbits substantially more energetic than the ones they had followed until turnaround. This mechanism seems to operate preferentially on low-mass satellites, as shown by the dashed histogram in Fig. 4, which corresponds to satellites with stellar masses less than \( \sim 3 \) per cent of the primary.

We highlight some of these objects in Fig. 3, using ‘filled’ circles to denote ‘associated’ satellites whose apocentres at \( z = 0 \) exceed their turnaround radii by at least 25 per cent. Two such objects are worth noting in this figure: one of them is the farthest ‘associated’ satellite, found at more than \( \sim 2.5 r_{vir} \) from the primary; the second

is an outward-moving satellite just outside the virial radius but with radial velocity approaching \( \sim 2V_{vir} \). The latter, in particular, is an extraordinary object, since its radial velocity alone exceeds the nominal escape velocity\(^2\) at that radius. This satellite is on a trajectory which, for all practical purposes, will remove it from the vicinity of the primary and leave it wandering through intergalactic space.

The origin of these unusual objects becomes clear when inspecting Fig. 2. The two satellites in question are shown with dashed lines in this figure; each is a member of a bound pair of satellites (the other member of the pair is shown with solid lines of the same colour). During first pericentric approach, the pair is disrupted by the tidal field of the primary and, while one member of the pair remains bound and follows the kind of ‘conventional’ orbit described in Section 3.1, the other one is ejected from the system on an extreme orbit. The trajectories of these two ‘ejected’ satellites in the \( r-V_t \) plane are shown by the wiggly lines in Fig. 3.

These three-body interactions typically involve the first pericentric approach of a bound pair of accreted satellites and tend to eject the lighter member of the pair; in the example of Fig. 2, the ‘ejected’ member makes up, respectively, only 3 and 6 per cent of the total mass of the pair at the time of accretion. Other interaction configurations leading to ejection are possible, such as an unrelated satellite that approaches the system during the late stages of a merger event, but they are rare, at least in our simulation series. We emphasize that not all satellites that have gained energy during accretion leave the system; most are just put on orbits of unusually large apo-centre but remain bound to the primary. This is shown by the filled circles in Fig. 3; many affected satellites are today completing their second or, for some, third orbit around the primary.

The ejection mechanism is perhaps best appreciated by inspecting the orbital paths of the satellite pairs. These are shown in Fig. 5, where the top (bottom) panels correspond to the satellite pair accreted later (earlier) into the primary in Fig. 2. Note that in both cases, as the pair approaches pericentre, the lighter member (dashed lines) is also in the process of approaching the pericentre of its own orbit around the heavier member of the pair. This coincidence in orbital phase combines the gravitational attraction of the two more massive members of the trio of galaxies, leading to a substantial gain in orbital energy by the lightest satellite, effectively ejecting it from the system on an approximately radial orbit. The heavier member of the infalling pair, on the other hand, decays on to a much more tightly bound orbit.

Fig. 5 also illustrates the complexity of orbital configurations that are possible during these three-body interactions. Although the pair depicted in the top panels approaches the primary as a cohesive unit, at pericentre each satellite circles about the primary in opposite directions: in the \( yz \) projection the heavier member circles the primary clockwise whereas the ejected companion goes about it counterclockwise. After pericentre, not only do the orbits of each satellite have different period and energy, but they differ even in the sign of their orbital angular momentum. In this case it would clearly

\(^2\) The notion of binding energy and escape velocity is ill defined in cosmology; note, for example, that the whole universe may be considered formally bound to any positive overdensity in an otherwise unperturbed Einstein–de Sitter universe. We use here the nominal escape velocity of an NFW model (Navarro, Frenk & White 1996, 1997) to guide the interpretation. This profile fits reasonably well the mass distribution of the primaries inside the virial radius, and has a finite escape velocity despite its infinite mass. Certainly satellites with velocities exceeding the NFW escape velocity are likely to move far enough from the primary to be considered true escapers.
in the top panels of Fig. 5, it should be clear from this figure and
shows the orbits in the rest frame of the primary. The coordinate system is
consistent so that the angular momentum of the primary is aligned with the
z axis. A solid curve tracks the path of the heavier satellite; a dashed line
follows the satellite that is propelled into a highly energetic orbit after.

be very difficult to link the two satellites to a previously bound pair
on the basis of observations of their orbits after pericentre.

Although not all ejections are as complex as the one illustrated
in the top panels of Fig. 5, it should be clear from this figure that
reconstructing the orbits of satellites that have been through pericentre
is extremely difficult, both for satellites that are ejected as well as
for those that remain bound. For example, the massive member
of the late-accreting pair in Fig. 2 sees its apocentre reduced
by more than a factor of 5 from its turnaround value in a single
pericentric passage. Such dramatic variations in orbital energy
are difficult to reproduce with simple analytic treatments inspired
on Chandrasekhar’s dynamical friction formula (Peña-Rubia, private
communication).

4 APPLICATION TO THE LOCAL GROUP

We may apply these results to the interpretation of kinematical outliers
within the satellite population around the Milky Way (MW)
and M31, the giant spirals in the Local Group. Although part of
the discussion that follows is slightly speculative due to lack of suitable
data on the three-dimensional orbits of nearby satellites, we feel that
it is important to highlight the role that the concomitant accretion
of multiple satellites may have played in shaping the dynamics of the
dwarf members in the Local Group.

4.1 Milky Way satellites

The filled squares in Fig. 3 show the galactocentric radial velocity
of thirteen bright satellites around the MW and compare them
with the simulated satellite population. This comparison requires a
choice for the virial radius and virial velocity of the MW, which are
observationally poorly constrained.

We follow here the approach of Sales et al. (submitted), and use
the kinematics of the satellite population itself to set the parameter
of the MW halo. These authors find that simulated satellites are
only mildly biased in velocity relative to the dominant dark matter component: \( \sigma_v \sim 0.9 \pm 0.2 \) \( V_{\text{vir}} \), where \( \sigma_v \) is the radial velocity dispersion of the satellite population within \( r_{\text{vir}} \). Using this, we find \( V_{\text{MW}} = 109 \pm 22 \) km s\(^{-1}\) and \( V_{\text{MW}} = 237 \pm 50 \) km from the observed radial velocity dispersion of \( \sim 98 \) km s\(^{-1}\). This corresponds to \( M_{\text{MW}} = 7 \times 10^{11} \) M\(_{\odot}\), in reasonable agreement with the 1–2 \( \times 10^{11} \) M\(_{\odot}\) estimate of Klypin, Zhao & Somerville (2002) and with the recent findings of Smith et al. (2006) based on estimates of the escape velocity in the solar neighbourhood.

Since Leo I has the largest radial velocity of the MW satellites,
we have recomputed the radial velocity dispersion excluding it from the sample. We have found that \( \sigma_v \) drops from 98 to 82 km s\(^{-1}\) when Leo I is not taken into account changing our estimation of \( V_{\text{MW}} \) from 109 to 91 km s\(^{-1}\), still within the errors of the value previously found. Given the recent rapid growth in the number of known MW satellite one would suspect that the velocity dispersion will significantly increase if more Leo I-like satellites are detected. However, we note that given their high velocities they are not expected to remain inside the virial radius for a long time period hence not contributing to the \( \sigma_v \) computation.

Fig. 3 shows that, considering \( V_{\text{MW}} = 109 \) km s\(^{-1}\), the velocities and positions of all MW satellites are reasonably consistent with the simulated satellite population, with the possible exception of Leo I, which is located near the virial radius and is moving outward with a velocity clearly exceeding \( V_{\text{vir}} \). Indeed, for \( V_{\text{MW}} = 109 \) km s\(^{-1}\), Leo I lies right on the escape velocity curve of an NFW profile with concentration parameter similar to those measured in the simulations. This is clearly a kinematical outlier reminiscent of the satellite expelled by three-body interactions discussed in the previous subsection and identified by a dot-centred circle in Fig. 3. This is the only ‘associated’ satellite in our simulations with radial velocity exceeding \( V_{\text{vir}} \) and located outside \( r_{\text{vir}} \).

Could Leo I be a satellite that has been propelled into a highly energetic orbit through a three-body interaction? If so, there are a number of generic predictions that might be possible to verify observationally. One is that its orbit must be now basically radial in the rest frame of the Galaxy, although it might be some time before proper motion studies are able to falsify this prediction. A second possibility is to try and identify the second member of the pair to which it belonged. An outward moving satellite on a radial orbit takes only \( \sim 2-3 \) Gyr to reach \( r_{\text{vir}} \) with escape velocity. Coincidentally, this is about the time that the Magellanic Clouds pair were last at pericentre, according to the traditional orbital evolution of the Clouds (see e.g. Gardiner & Noguchi 1996; van der Marel et al. 2002).

Could Leo I have been a Magellanic Cloud satellite ejected from the Galaxy a few Gyr ago? Since most satellites that are ejected do so during first pericentric approach, this would imply that the Clouds were accreted only recently into the Galaxy, so that they reached their first pericentric approach just a few Gyr ago. This is certainly in the spirit of the reanalysis of the orbit of the Clouds presented recently by Besla et al. 2007 and based on new proper motion measurements recently reported by Kallivayalil et al. (2006). In this regard, the orbit of the Clouds might resemble the orbit of the companion of the ‘escaping’ satellite located next to Leo I in Fig. 3. The companion is fairly massive and, despite a turnaround radius of almost \( \sim 600 \) kpc and a rather late accretion time \( t_{\text{acc}} = 10.5 \) Gyr, see Fig. 2), it is left after pericentre on a tightly bound, short-period orbit resembling that of the Clouds today (Gardiner & Noguchi 1996; van der Marel et al. 2002). To compound the resemblance, this satellite has, at accretion time, a total luminosity...
of the order of \(\sim 10\) per cent of that of the primary, again on a par with the Clouds.

We also note that an ejected satellite is likely to have picked up its extra orbital energy through a rather close pericentric passage and that this may have led to substantial tidal damage. This, indeed, has been argued recently by Sohn et al. 2006 on the basis of asymmetries in the spatial and velocity distribution of Leo I giants (but see Koch et al. 2007 for a radically different interpretation).

On a final note, one should not forget to mention another (less exciting!) explanation for Leo I: that our estimate of \(V_{\text{vir}}\) is a substantial underestimate of the true virial velocity of the MW. The arrows in Fig. 3 indicate how the position of the MW satellites in this plane would change if our estimate of \(V_{\text{vir}}\) is varied by \(\pm 20\) per cent. Increasing \(V_{\text{vir}}\) by \(\sim 20\) per cent or more would make Leo I’s kinematics less extreme, and closer to what would be expected for a high-speed satellite completing its first orbit. This rather more prosaic scenario certainly cannot be discounted on the basis of available data (see e.g. Zaritsky et al. 1989; Kochanek 1996; Wilkinson & Evans 1999).

### 4.2 M31 satellites

A similar analysis may be applied to M31 by using the projected distances and line-of-sight velocities of simulated satellites, shown in Fig. 6. Three orthogonal projections of the simulated satellites are overlapped in this figure, with symbols as defined in Fig. 3. Following the same approach as in Section 4.1, we use the fact that the line-of-sight satellite velocity dispersion is \(\sigma_{\text{los}} \sim 0.8(\pm 0.2)V_{\text{vir}}\) in our simulations to guide our choice of virial velocity and radius for M31; \(V_{\text{vir}}^{\text{M31}} = 138 \pm 35\ \text{km s}^{-1}\) and \(r_{\text{vir}}^{\text{M31}} = 300 \pm 76\) kpc. (We obtain \(\sigma_{\text{los}} = 111\ \text{km s}^{-1}\) for all 17 satellites within 300 kpc of M31). This compares favourably with the \(V_{\text{vir}}^{\text{M31}} \sim 120\ \text{km s}^{-1}\) estimate recently obtained by Seigar, Barth & Bullock (2006) under rather different assumptions.

With this choice, we show the 19 satellites around M31 compiled by McConnachie & Irwin (2006), plus two recently discovered satellites for which positions and radial velocities have become available (And XII, Chapman et al., submitted, and And XIV, Majewski et al. 2007). As in Fig. 3, arrows indicate how the position of M31 satellites would change in this figure if \(V_{\text{vir}}\) were allowed to vary by \(\pm 20\) per cent. We note that the exclusion of And XII and And XIV (the highest velocity satellites within 300 kpc from Andromeda) in the \(V_{\text{vir}}^{\text{M31}}\) estimation gives \(\sim 100\ \text{km s}^{-1}\), consistent with the \(V_{\text{vir}}^{\text{M31}} = 138 \pm 35\ \text{km s}^{-1}\) previously found considering all satellites. Projected distances are as if viewed from infinity along the direction joining the MW with M31 and that the sign of the line-of-sight velocity in Fig. 6 is chosen to be positive if the satellite is receding from the primary (in projection) and negative otherwise.

There are a few possible outliers in the distribution of M31 satellite velocities: And XIV (Majewski et al. 2007), the Pegsus dwarf irregular (UGC 12613, Gallagher et al. 1998), And XII (Chapman et al., submitted), and UGCA 092 (labelled U092 in Fig. 6, McConnachie & Irwin 2006). And XIV and PegDIG seem likely candidates for the three-body ‘ejection’ mechanism discussed above: they have large velocities for their position, and, most importantly, they are receding from M31; a requirement for an escaping satellite. Note, for example, that And XIV lies very close to the ‘escaping’ satellite (dot-centred symbol in Fig. 6) paired to Leo I in the previous subsection. Escapers should move radially away from the primary, and they would be much harder to detect in projection as extreme velocity objects, unless they are moving preferentially along the line of sight. It is difficult to make this statement more conclusive without further knowledge of the orbital paths of these satellites. Here, we just note, in agreement with Majewski et al. (2007), that whether And XIV and PegDIG are dynamical ‘rogues’ depends not only on the (unknown) transverse velocity of these galaxies, but also on what is assumed for M31’s virial velocity. With our assumed \(V_{\text{vir}}^{\text{M31}} = 138\ \text{km s}^{-1}\), neither And XIV nor PegDIG looks completely out of place in Fig. 6; had we assumed the lower value of 120 km s\(^{-1}\) advocated by Seigar et al. (2006) And XIV would be almost on the NFW escape velocity curve, and would certainly be a true outlier.

High-velocity satellites approaching M31 in projection are unlikely to be escapers, but rather satellites on their first approach. This interpretation is probably the most appropriate for And XII and UGCA 092. As discussed by Chapman et al. (submitted), And XII is almost certainly farther than M31 but is approaching us at much higher speed (\(\sim 281\ \text{km s}^{-1}\)) faster than M31. This implies that And XII is actually getting closer in projection to M31 (hence the negative sign assigned to its \(V_{\text{vir}}\) in Fig. 6), making the interpretation of this satellite as an escaping system rather unlikely.

Note, again, that although And XII (and UGCA 092) are just outside the loci delineated by simulated satellites in Fig. 6, revising our assumption for \(V_{\text{vir}}^{\text{M31}}\) upward by 20 per cent or more would render the velocity of this satellite rather less extreme, and would make it consistent with that of a satellite on its first approach to M31. As was the case for Leo I, this more prosaic interpretation of the data is certainly consistent with available data.

### 5 SUMMARY AND CONCLUSIONS

We examine the orbits of satellite galaxies in a series of N-body/gasdynamical simulations of the formation of \(L_\star\) galaxies in a

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**Figure 6.** As Fig. 3 but for line-of-sight velocities and projected distances. Three random orthogonal projections have been chosen for each simulated satellite system. Signs for \(V_{\text{los}}\) have been chosen so that it is positive if the satellite is receding away from the primary in projection, negative otherwise. The ‘escaping’ satellite from Fig. 3 is shown by a starred symbol. Filled squares correspond to the M31 satellites taken from McConnachie & Irwin 2006, plus And XIV (Majewski et al. 2007) and And XII (Chapman et al., submitted) and assuming that \(V_{\text{vir}} \sim 138\ \text{km s}^{-1}\) and \(V_{\text{vir}}^{\text{M31}} = 300\ \text{kpc}\). Arrows indicate how the positions of M31 satellites in this plot would be altered if our estimate of \(V_{\text{vir}}^{\text{M31}}\) (and, consequently, \(V_{\text{vir}}\)) is allowed to vary by 20 per cent.
ACDM universe. Most satellites follow orbits roughly in accord with the expectations of secondary infall-motivated models. Satellites initially follow the universal expansion before being decelerated by the gravitational pull of the main galaxy, turning around and accreting on to the main galaxy. Their apocentric radii decrease steadily afterwards as a result of the mixing associated with the virialization process as well as of dynamical friction. At $z = 0$ most satellites associated with the primary are found within its virial radius, and show little spatial or kinematic bias relative to the dark matter component (see also Sales et al., submitted).

A number of satellites, however, are on rather unorthodox orbits, with present apocentric radii exceeding their turnaround radii, at times by a large factor. The apocentres of these satellites are typically beyond the virial radius of the primary; one satellite is formally `unbound’, whereas another is on an extreme orbit and is found today more than $2.5r_{\text{vir}}$ away, or $\geq 600$ kpc when scaling this result to the MW.

These satellites owe their extreme orbits to three-body interactions during first approach: they are typically the lighter member of a pair of satellites that is disrupted during their first encounter with the primary. This process has affected a significant fraction of satellites: a full one-third of the simulated satellite population identified at $z = 0$ have apocentric radii exceeding their turnaround radii. These satellites make up the majority (63 per cent) of systems on orbits that venture outside the virial radius.

We speculate that some of the kinematical outliers in the Local Group may have been affected by such process. In particular, Leo I might have been ejected 2–3 Gyr ago, perhaps as a result of interactions with the MW and the Magellanic Clouds. Other satellites on extreme orbits in the Local Group may have originated from such mechanism. Cetus (Lewis et al. 2007) and Tucana (Oosterloo, Da Costa & Staveley-Smith 1996) – two dwarf spheroidals in the periphery of the Local Group – may owe their odd location (most dSphs are found much closer to either M31 or the Galaxy) to such ejection mechanism.

If this is correct, the most obvious culprits for such ejection events are likely to be the largest satellites in the Local Group (M33 and the Large/Small Magellanic Clouds), implying that their possible role in shaping the kinematics of the Local Group satellite population should be recognized and properly assessed. In this regard, the presence of kinematical oddities in the population of M31 satellites, such as the fact that the majority of them lie on `one side' of M31 and seem to be receding away from it (McConnachie & Irwin 2006), suggest the possibility that at least some of the satellites normally associated with M31 might have actually been brought into the Local Group fairly recently by M33. Note, for example, that two of the dynamical outliers singled out in our discussion above (And XII and And XIV) are close to each other in projection; have rather similar line-of-sight velocities (in the heliocentric frame And XII is approaching us at 556 km s$^{-1}$, And XIV at 478 km s$^{-1}$); and belong to a small subsystem of satellites located fairly close to M33.

The same mechanism might explain why the spatial distribution of at least some satellites, both around M31 and the MW, seem to align themselves on a `planar' configuration (Majewski 1994; Libeskind et al. 2005; Koch & Grebel 2006), as this may just reflect the orbital accretion plane of a multiple system of satellites accreted simultaneously in the recent past (Kroupa, Theis & Boily 2005; Metz, Kroupa & Jerjen 2007).

From the point of view of hierarchical galaxy formation models, it would be rather unlikely for a galaxy as bright as M33 to form in isolation and to accrete as a single entity on to M31. Therefore, the task of finding out which satellites (rather than whether) have been contributed by the lesser members of the Local Group, as well as what dynamical consequences this may entail, should be undertaken seriously, especially now, as new surveys begin to bridge our incomplete knowledge of the faint satellites orbiting our own backyard.

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