The dynamics of tidal tails from massive satellites

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ABSTRACT

We investigate the dynamical mechanisms responsible for producing tidal tails from dwarf satellites using $N$-body simulations. We describe the essential dynamical mechanisms and morphological consequences of tail production in satellites with masses greater than 0.0001 of the host halo virial mass. We identify two important dynamical coconspirators: (1) the points where the attractive force of the host halo and satellite are balanced (X-points) do not occur at equal distances from the satellite centre or at the same equipotential value for massive satellites, breaking the morphological symmetry of the leading and trailing tails and (2) the escaped ejecta in the leading (trailing) tail continues to be decelerated (accelerated) by the satellite’s gravity leading to large offsets of the ejecta orbits from the satellite orbit. The effect of the satellite’s self-gravity decreases only weakly with a decreasing ratio of satellite mass to host halo mass, proportional to $(M_s/M_h)^{1/3}$, demonstrating the importance of these effects over a wide range of subhalo masses. Not only will the morphology of the leading and trailing tails for massive satellites be different, but the observed radial velocities of the tails will be displaced from that of the satellite orbit; both the displacement and the maximum radial velocity is proportional to satellite mass. If the tails are assumed to follow the progenitor satellite orbits, the tails from satellites with masses greater than 0.0001 of the host halo virial mass in a spherical halo will appear to indicate a flattened halo. Therefore, a constraint on the Milky Way halo shape using tidal streams requires mass-dependent modelling. Similarly, we compute the distribution of tail orbits both in $E_r−r^2$ space and in $E−L_z$ space, advocated for identifying satellite stream relics. The acceleration of ejecta by a massive satellite during escape spreads the velocity distribution and obscures the signature of a well-defined ‘moving group’ in phase space. Although these findings complicate the interpretation of stellar streams and moving groups, the intrinsic mass dependence provides additional leverage on both halo and progenitor satellite properties.

Key words: methods: $N$-body simulations – methods: numerical – galaxies: evolution – galaxies: haloes – galaxies: interaction – galaxies: kinematics and dynamics.

1 INTRODUCTION

According to the currently favoured galaxy formation scenario, the cold dark matter (CDM) cosmogony, galaxies are built up from the assembly of small structures. In this paradigm the assembly mechanism plays a key role in understanding the formation history of galaxies. Recent CDM cosmological numerical simulations predict the existence of a large population of subhaloes. Comparisons with the observed population of dwarf galaxies and detailed predictions of the present-day subhalo population, dark or luminous, have become important tests of the CDM galaxy formation paradigm (Ghigna et al. 1998, 2000; De Lucia et al. 2004; Diemand, Moore & Stadel 2004; Gao et al. 2004; Oguri & Lee 2004). Most studies to date use large cosmological simulations and classify their properties statistically. However, to properly investigate these processes, one needs to perform high-resolution idealized simulations of subhalo evolution within the CDM paradigm (Hayashi et al. 2003). Alternatively, in this study, we investigate one important consequence of subhalo disruption: the formation and evolution of tidal tails. By adopting initial conditions motivated by the CDM simulations, we can focus our computational resources on understanding the dynamical mechanism.

Satellite galaxy tidal tails are an important observable fossil signature to help understand the formation history of the Milky Way and to test CDM theory as a consequence. Tails and streams provide information about the Galactic halo mass model as well as the evolutionary history of the observed satellite galaxy. In the CDM model, galaxies are embedded in massive dark matter haloes. Estimating dark matter halo structure is essential to understand galaxy formation and tidal tail morphology probe halo structure (Johnston
et al. 1999; Helmi & de Zeeuw 2000; Ibata et al. 2001a,b). Several space missions, e.g. the ESA astrometric satellite GAIA (Lindegren & Perryman 1996; Perryman et al. 2001), are planned to measure the position and motion of stars in the Milky Way with very high accuracy, in the near future. Together with ground-based radial velocity experiments, e.g. RAVE\(^1\) (Steinmetz et al. 2006), these surveys will provide full phase-space information. Accurate six-dimensional phase-space information of Milky Way stars will provide observational information of the tidal tail and hence the formation history of the Milky Way. The time is ripe to carry out a detailed theoretical study of satellite galaxy disruption and the induced tidal tail morphology.

In this study we perform numerical simulations of satellite galaxy disruption and its induced tidal tail morphology within the CDM cosmogony. The objective of this study is to understand the physical processes responsible for satellite galaxy disruption rather than reproducing the evolutionary history of any individual Milky Way satellite galaxy. In particular, satellite disruption in N-body simulations is produced by escaping satellite particles. In addition, the gravitational shock, which is caused by the slowly varying host halo potential as the satellite goes through its orbit, changes the satellite’s internal structure. An initially stable satellite galaxy and accurate numerical integration of a satellite particle’s orbit are necessary to represent these physical processes correctly. We investigate satellite galaxy evolution by performing high-resolution and low-noise N-body simulations with such stable initial conditions.

In addition, we can estimate any trends of satellite tidal tail morphology with satellite properties from our simulations, even though we do not reproduce the evolutionary history of any specific Milky Way satellite galaxy. Our simulation results show that the gravity of the satellite alters the location of the tidal tails relative to the satellite orbit. The satellite decelerates (accelerates) the leading (trailing) tail beyond the tidal radius, which is proportional to the mass of the satellite. For more massive satellites, this results in the leading tail being located well inside and the trailing tail being located well outside of the satellites orbit, rather than tracking the original satellite orbit (Moore & Davis 1994; Johnston, Hernquist & Bolte 1996; Johnston, Sackett & Bullock 2001). Since the satellite torques the tidal tail, the distribution of the tidal tail in the observational plane is rather different from predictions that exclude such satellite torquing. In addition, the simulations provide six-dimensional phase-space information of the tidal tail to compare with upcoming astrometric measurements.

In Section 2, we describe how we make stable satellite initial conditions and provide a brief overview of the simulation algorithm. In Section 3, we investigate satellite disruption and the formation of the tidal tail, including the effects of the satellite potential on the tidal tail and in Section 4, we investigate the observational consequences. In Section 5, we summarize our results and discuss their importance.

### 2 INITIAL CONDITIONS AND N-BODY METHODOLOGY

The initial conditions of our simulations are motivated by the CDM cosmology. CDM cosmological simulations suggest that dark matter haloes have a universal density profile (Navarro, Frenk & White 1997, hereafter NFW), \(\rho(r) \propto r^{-1} \left( r + r_s \right)^{-2} \), where \(r_s\) is a scale-length characterized by the concentration parameter \(c = R_{15}/r_s\) and \(R_{15}\) is the virial radius of the halo. Although there are some disagree-

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\(^1\) See http://www.rave-survey.org.
different size satellites, which we refer to as the massive satellite, the low-mass satellite, and the tiny-mass satellite. We use the maximum rotation velocity, $v_{\text{max, host}}$, as a measure of satellite size since the continuous mass-loss makes mass an inexact measure. We use a $v_{\text{max, host}}$ of 0.45, 0.16 and 0.08 times $v_{\text{max, host}}$ for the massive, low-mass and tiny-mass, respectively. The tidal distance for all three satellites is 0.4 $R_{\text{vir, host}}$. We also set the galactocentric orbital radius to 0.4 $R_{\text{vir, host}}$ for our circular orbit simulations. After our truncation procedure is complete, the initial mass of the massive satellite is 0.018 $M_{\text{host}}$, the low-mass satellite 0.001 $M_{\text{host}}$, and the tiny-mass satellite 0.0001 $M_{\text{host}}$. Converting our simulation units to a Milky Way size galaxy system and evolving for a few satellite orbits, the low-mass satellite roughly corresponds in mass to the Sagittarius dwarf galaxy halo (Majewski et al. 2004; Law, Johnston & Majewski 2005). The massive and tiny-mass satellites are an order of magnitude more and less massive, respectively. The properties of these satellite haloes is summarized in Table 1 in units of the virial quantities of the host halo. All satellite initial conditions in this study have $10^6$ particles.

We evolve each of the three satellites on three different orbits with the same energy but with different eccentricities. We define the eccentricity of the orbits as $e = (r_a - r_p)/(r_a + r_p)$ where $r_a$ and $r_p$ are the apocentre and the pericentre of a satellite. The first orbit is circular ($e = 0$) at 0.4 $R_{\text{vir}}$. The second orbit has an $e = 0.5$ with a pericentre of 0.2 $R_{\text{vir}}$ and an apocentre of 0.6 $R_{\text{vir}}$ and the third orbit has $e = 0.74$ with a pericentre of 0.1 $R_{\text{vir}}$ and an apocentre of 0.67 $R_{\text{vir}}$. The third orbit is particularly relevant cosmologically since its circularity ($\kappa^2$) is 0.5, which is the median $\kappa$ of subhaloes in a sample taken from recent cosmological simulations (Ghigna et al. 1998; Zentner et al. 2005). We quote results using the following system units unless otherwise specified: $G = 1$, $M_{\text{vir, host}} = 1$ and $R_{\text{vir, host}} = 1$.

**Table 1.** Initial properties of the three satellite models.

<table>
<thead>
<tr>
<th>Satellite</th>
<th>$M/M_{\text{vir, host}}$</th>
<th>$R/R_{\text{vir, host}}$</th>
<th>$V_{\text{max}}/V_{\text{max, host}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Massive</td>
<td>$1.9 \times 10^{-2}$</td>
<td>$9.02 \times 10^{-2}$</td>
<td>0.45</td>
</tr>
<tr>
<td>Low-mass</td>
<td>$9.0 \times 10^{-4}$</td>
<td>$3.38 \times 10^{-2}$</td>
<td>0.16</td>
</tr>
<tr>
<td>Tiny-mass</td>
<td>$9.9 \times 10^{-5}$</td>
<td>$1.66 \times 10^{-2}$</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Figure 1. The effect of our truncation procedure (see text) on a satellite’s initial NFW profile. (a) The enclosed mass profile. (b) The effective potential profile. (c) The distribution function versus energy. (d) The circular velocity profile. We use system units unless otherwise specified: $G = 1$, $M_{\text{vir, host}} = 1$ and $R_{\text{vir, host}} = 1$.}

Figure 2. Comparison of the evolved density profiles of two identical, low-mass satellite haloes evolved with different starting radii. The inner orbit begins with $r = 0.67 R_{\text{vir}}$ and a tidal distance corresponding to 0.4 $R_{\text{vir}}$ with an eccentricity $e = 0.73$. The virial radius orbit begins with $r = 1.0 R_{\text{vir}}$ and a tidal distance corresponding to 1.0 $R_{\text{vir}}$ with $e = 0.5$. Owing to gravitational heating, the evolution of the two satellites is different but the profiles approximately agree when the total mass-loss is the same.

\[ \kappa = J/J_c, \] where $J$ is the angular momentum and $J_c$ is the angular momentum of a circular orbit with the same energy.
For the gravitational potential solver, we use a three-dimensional self-consistent field algorithm (also known as an expansion algorithm, e.g. Clutton-Brock 1972, 1973; Hernquist & Ostriker 1992; Weinberg 1999). This algorithm produces a bi-orthogonal basis set of density-potential pairs from which it computes the gravitational potential of an $N$-body system, given the mass and positions of the particles. For an arbitrary basis, e.g. spherical Bessel functions, the expansion generally requires a large number of terms to achieve convergence, which introduces small-scale noise as well as requiring greater computational expense. The situation was dramatically improved by Weinberg (1999) using a numerical solution of the Sturm-Liouville equation to match the lowest order pair to the equilibrium profile, and therefore, the expansion series converges rapidly. Here, we use the current density profile as the zero-order basis function.

For our purposes, this expansion algorithm is attractive for two reasons. First, the expansions can be chosen to follow structure over an interesting range of scales and simultaneously suppresses small-scale noise. In contrast, noise from two-body scattering can arise at all scales in direct summation, tree algorithm and mesh-based codes. Small-scale scattering can give rise to a diffusion in conserved quantities, which can lead to unphysical outcomes particularly for studies of long-term galaxy evolution (see Weinberg & Katz 2007a,b). Secondly, the expansion algorithm is computationally efficient; the computational time only increases linearly with particle number. Hence, the expansion algorithm permits the use of a much larger number of particles than most other algorithms for the same computational cost.

An accurate potential solver for a cuspy halo demands a precise determination of the expansion centre, $C$. This is the major disadvantage of the expansion algorithm relative to a Lagrangian potential solver such as a tree code. We developed and tested the following algorithm for evolving cuspy dark matter haloes with an expansion code.

(i) At time-step $n$, we compute $C_n$ from the centre of mass of the $N_{\text{max}}$ most bound particles.

(ii) To evaluate the expansion centre at time-step $n + 1$, a predicted centre $C_{\text{pred}}$ is estimated from a linear least-squares solution using the previous $N_{\text{keep}}$ centres: $\{ C_{j} \}, n - N_{\text{keep}} < j \leq n$.

(iii) For $n < 2$, we set $C_{\text{pred}} = C_n$.

(iv) To reduce truncation error, we separately track the motion relative to the satellite’s centre and the motion of the centre itself.

The linear least-squares estimator for the expansion centre $C_{\text{pred}}$ reduces the Poisson noise from the $N_{\text{min}}$ particles used to determine each of the $C_n$. For our simulations we have adopted $N_{\text{min}} = 512$ and $N_{\text{keep}} = 10$ and have verified that this centring scheme maintains the cusp while the satellite orbits in a host halo for situations where the tidal field is insignificant.

3 THE MORPHOLOGY OF SATELLITE TIDAL TAILS

Time-dependent forcing by the host halo's tidal field adds energy to the satellite, driving mass-loss and, ultimately, disruption. These forces are a combination of the differential force from the host halo and the non-inertial forces from the satellite orbit. The work done against the satellite’s gravitational potential results in mass-loss. In addition, these forces deform the outer density contours of the satellite. To understand the evolution of the ejecta, one must also consider the gravitational field of the satellite. The gravitational force from the satellite decelerates (accelerates) the leading (trailing) tail, modifying the energy and angular momentum of the ejecta well past the point of escape. The conserved quantities of the ejecta, then, may be dramatically different than that of the satellite centre of mass. The strength of the satellite gravity increases with satellite mass, of course. These effects combine to make the morphology of tidal tails more complicated than previously suggested (Moore & Davis 1994; Ibata & Lewis 1998; Helmi & White 1999; Johnston et al. 2001; Mayer et al. 2002), especially for a massive satellite. We investigate the causes of these effects and their consequences in detail below.

3.1 Satellite disruption

We begin by describing the dynamics and morphology of the tidal tails in a simulation that ignores the gravitational field of the satellite past the tidal radius. Fig. 3 shows a sequence of snapshots of the low-mass satellite (0.001 $M_{\text{host}}$) on a circular orbit at 0.4$R_{\text{vir}}$. We use units where $M_{\text{vir}} = 1$, $R_{\text{vir}} = 1$ and Newton’s gravitational constant $G = 1$, together which defines a natural time-unit. Scaled to the Milky Way, 0.5 natural time-units is approximately 1 Gyr. Appealing to the standard zero-velocity Roche potential, which balances the effective gravitational potential in the rotating frame with the halo potential, we expect the mass to become unbound in the vicinity of the Lagrange or X-points. Indeed, we observe the double cometary appearance of tails leading and trailing the satellite, enforced by the conservation of angular momentum. For this halo model, the leading ejecta orbits faster than the satellite and has a position angle of $300^\circ$ measured from the positive vertical axis, the direction of satellite’s instantaneous motion. The trailing tail moves slower than the satellite and has a position angle of $120^\circ$. Since the simulation in Fig. 3 ignores the satellite’s gravity beyond the tidal radius, the orbit of the tidal tail merely represents the kinematic condition of the tail material just when it escapes from the satellite.

![Figure 3. The mass density of the low-mass satellite on a circular orbit with $r = 0.4R_{\text{vir}}$ at $T = 0.0$ (top left-hand part), 1.5 (top right-hand part), 3.0 (bottom left-hand part) and 4.5 (bottom right-hand part). Recall that the orbital period for the circular orbit in this simulation is $T_{\text{period}} \approx 2.0$. The colour scale is logarithmic in the dark matter mass density, increasing from blue to red, and is fixed for all times $T$. Each panel has a linear size of two host halo virial radii. For this simulation, the tail particles do not feel the gravitational force of the satellite after escape. The circles show the satellite orbit. The multiple streams in the tail owe to phase crowding near apocentre for initially prograde and retrograde orbits.](https://academic.oup.com/mnras/article-abstract/381/3/987/1062559)
A simple easy-to-compute prescription for the tails' angular momentum of a tail is the same as those of a satellite; this yields a massless description of tail formation. More specifically, the orbital energy and angular momentum lost during the escape changes the conserved quantities of the ejecta from that of the satellite orbit; the leading (trailing) ejecta lose (gain) energy during deformation. Moreover, the distribution of the tails fills a wide region about the satellite orbit. This reflects the broad distribution of phases for orbits at escape. Hence, the width of the tail is nearly the same as the distance between the apocentre and the pericentre of a typical rosette orbit. Each tail has several distinct streamers filling a common envelope. The two primary streams in each tail demarcate the escape of the most extreme prograde and retrograde orbits. The originally prograde orbits have lower specific angular momentum and, therefore, smaller pericentres and larger epicyclic amplitudes. In contrast, originally retrograde orbits have larger pericentres and smaller epicyclic amplitudes. Distinct streamers result from the phase caustics near apocentre, similar to shells in elliptical galaxies caused by merger ejecta with a velocity dispersion much smaller than its new orbital velocity. This mechanism, illustrated in Fig. 3, is the massless description of tail formation. This massless description assumes that the orbital energy and angular momentum of a tail is the same as those of a satellite; this yields a simple easy-to-compute prescription for the tails' location.

In contrast, Fig. 5 repeats the simulation including the gravity of both the halo and the satellite at all times. At early times (upper right-hand panel), the evolution is similar. However, at later times (lower panels), the effects of the satellite gravity are marked. The continued acceleration of the tail by the satellite after escape decreases the internal velocity dispersion and narrows or focuses the tail as a consequence. The streamers in Fig. 3 become less distinct when accelerated by the gravity of the satellite and the host halo together for the same reason (see Fig. 6). Similarly, the acceleration of the ejecta by the satellite also decreases the angular separation between the streamers. Although the multistreamer feature is diminished as the satellite gravitational field accelerates the ejecta, the feature can still be seen very close to the tidal radius.

### 3.2 Tail evolution

#### 3.2.1 Circular orbits

The importance of a satellite's gravity increases with mass and, therefore, we begin with a study of the tail produced by a massive satellite. Fig. 7 shows snapshots of a massive satellite (0.018 $M_{\text{host}}$) on a circular orbit at $0.4R_{\text{vir}}$, where once again the tail particles always feel the gravitational force from the satellite. The overall evolution of the satellite and its disruption time is similar to the less massive satellite shown in Fig. 5. However, the long-term acceleration of the ejected material by the remaining satellite significantly alters these orbits. As the tail continues to lose mass, the leading and trailing tails evolve to positions that are well inside and well outside the satellite's orbit and hence does not trace the satellite orbit at all (Moore & Davis 1994; Johnston et al. 2001). The leading tail...
Figure 7. The mass density in the orbital plane for a massive satellite halo on a circular orbit with \( r = 0.4 \, R_{\text{vir}} \) at \( T = 0.0, 1.0, 2.0, 3.0 \) and 4.0 in the top left-hand, top right-hand, middle left-hand, middle right-hand and bottom left-hand panels, respectively. Recall that the orbital period of the circular orbit is \( T_{\text{period}} \sim 2.0 \). The bottom right-hand panel shows the edge on view at \( T = 4.0 \). The colour scale is logarithmic in the dark matter mass density from blue to red. The colour scale is fixed for all snapshots (as described in Fig. 3). The circles show the satellite orbit. The tail remains confined to the orbital plane as expected (lower right-hand panel).

significantly tilts towards the centre of the halo and almost points directly there at late times. The trailing tail is distributed throughout a wide annulus in the outer halo. This difference results from the torque applied by the satellite well after escape. Orbits in the leading tail that lose energy and angular momentum fall towards the centre of halo, while orbits in the trailing tail gain energy and angular momentum and spread over a wide range of radii in the outer halo.

We show the tail morphology for our satellites with three different masses (see Table 1) on circular orbits at \( T = 4 \) in Fig. 8. The tidal tails in the low-mass and tiny-mass satellites (0.001 and 0.0001 \( M_{\text{host}} \), respectively) very roughly follow the satellite orbit, with the leading and trailing tail located inside and outside of the satellite orbit. Compared to Fig. 3, it is clear that the differences decrease with the satellite mass. As we described in Section 2, the low-mass satellite corresponds to the Sagittarius dwarf spheroidal galaxy halo and the tiny-mass satellite corresponds to the Draco dwarf spheroidal galaxy halo.

Fig. 9 shows the evolution of the distance from the host halo centre and the satellite’s gravitational potential for an ensemble average of 10 randomly sampled particles near the tip of the leading tail in the three satellites. The tail from a massive satellite receives a larger torque and a larger shift to smaller energies and angular momentum than the tail from a lower mass satellite. The bottom panel in Fig. 9 shows that the decay results from interactions with
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Figure 8. As in Fig. 7 but comparing the ejecta at $T = 4.0$ for the massive, low-mass and tiny-mass satellites from left- to right-hand panels, respectively.

Figure 9. The evolution of the mean radius (top panel) and satellite potential (lower panel) for an ensemble of particles randomly selected from the leading tails in Fig. 8 for the massive (solid line), low-mass (dotted line), and tiny-mass (dash-dotted line) satellites.

The leading tail from the low-mass and the tiny-mass satellites in Fig. 8 exhibits kinks. The kinks are a consequence of the epicyclic motion of the tail orbits and of acceleration by the satellite at subsequent apocentres. Fig. 10 shows the ensemble averaged distance and positions for a sample of leading tail particles orbits taken from the low-mass satellite simulation shown in Fig. 5. The kink occurs at the first apocentre of the ejecta, after it is decelerated by the satellite during and subsequent to its escape. The deceleration during escape tends to correlate the phases of the ejected orbits and results in a narrowing of the tidal tail’s width. In contrast, the satellite potential accelerates the trailing tail particles, which increases the pericentre and apocentre of the trailing tail. The analogous kink in the trailing tail is not so obvious because of its lower orbital frequencies. However, a plot analogous to Fig. 10 does show a similar oscillation with lower angular frequency.

The large changes in the orbits of escaping particles orbits are easily understood using a restricted three-body approach. Consider a satellite of mass $M_s$ in circular orbit at galactocentric radius $r_s$ in a halo of mass $M_h$. In the frame of reference moving with a satellite of vanishingly small mass, the effective potential is symmetric about the satellite centre. Although orbital energy and angular momentum are not conserved, this system admits a conserved quantity, the Jacobi constant:

$$E_J = E - \frac{\Omega_s}{\Omega_1} \cdot L,$$

(1)

where $E$ and $L$ are the orbital energy and angular momentum and $\Omega_s$ is the satellite’s angular frequency about the host halo. This expression is easily derived by identifying a perfect time derivative in the inner product of the velocity vector and Newton’s equations of motion in the rotating frame of reference (Binney & Tremaine 1987, section 3.3.2). An isocontour of the Jacobi constant passes through the X-points, $r_\times$, and demarcates the bound and unbound trajectories as shown in Fig. 11(a). As the satellite mass increases, the inversion symmetry about the satellite centre is broken and the...
unsatisfactory points separate as shown in Fig. 11(b). For small-mass satellites, therefore, the tidal force is symmetric about the satellite centre leading to symmetric tidal tails as seen in globular clusters. However, for large-mass satellites, the asymmetry in the tidal force leads to asymmetric mass-loss.

Now consider the mass lost through the inner (outer) critical point, \( r_s \). Such orbits will have an inward (outward) velocity and unbound values of the Jacobi constant. The force from the satellite continues to affect the orbit beyond the tidal radius in this restricted problem as in the N-body simulations. Moreover, the smaller the mass of the satellite, the closer the radius is to that of the satellite, and the ejected orbit lingers near the original satellite orbit, partly offsetting the smaller gravitational force. For this reason, the orbit does not take on the orbital actions of the satellite but continues to be torqued by the satellite. One may estimate the scaling of this energy change by computing the work done in the satellite frame on the escaping tail particle; this naturally takes into account the lingering. Begin with the standard restricted three-body problem with generalized forces. Assuming that the satellite orbits in the \( x\bar{y} \) plane and using Hamilton’s equations, one may compute the \( z \)-component torque on an escaping particle and the change in angular momentum of the escaping particle after an interval \( T \) becomes

\[
\Delta L_z = \int_0^T \frac{\partial H}{\partial \phi} \left( \frac{\partial H}{\partial r} \right) = \int_0^T \frac{\partial V_z}{\partial \phi},
\]

where \( H \) is the Hamiltonian, \( \phi \) is the azimuthal coordinate conjugate to \( L_z \) and

\[
V_z = -\frac{GM_s}{|r - r_s(t)|}
\]
is the gravitational potential of the satellite. The second equality in equation (2) owes to the \( \phi \) independence of all the other terms in \( H \). We may consider an escaping orbit in the limit that the mass of the satellite \( M_s \) is much smaller than the mass of halo \( M_h \) and use perturbation theory to evaluate equation (2). To do this, let the unperturbed orbit be the circular orbit that passes through the X-point, \( r_s \) at \( t = 0 \). Expanding to lowest contributing order in \( M_s/M_h \), after some straightforward algebra and taking the limit \( T \to \infty \), one may show that

\[
\Delta L_z = \frac{GM_s}{r_s} \left( \frac{\partial \Omega_s}{\partial r} \left| \frac{1}{r_s} \right. \right)^{-1},
\]

where \( \Omega_s \) is the azimuthal orbital frequency. Finally, it follows that

\[
\Delta E = \Omega_s \Delta L_z \frac{1}{\Omega_s} = \frac{M_s}{M_h} \frac{1}{\Omega_s} \left( \frac{M_s}{M_h} \right)^{1/3},
\]

Since \( G, r_s \) and \( \Omega_s \) are constant, equation (3) implies that the work done is proportional to \( (M_s/M_h)^{1/3} \). In other words, the change in the orbital energy of the escaping particle decreases as the satellite mass decreases but only weakly!

Although the derivation of the scaling assumes \( M_s/M_h \to 0 \), we demonstrate numerically that it applies over all values of interest by integrating the equations of motion in the rotating potential. We adopt \( r_s = 0.4 \) and choose values of the Jacobi constant that are 1 per cent larger than the critical value passing through \( r_s \) with zero velocity. The initial motion, in the rotating frame, is along (or against) the direction of rotation for inner (outer) escapes. Figs 12–14 show the resulting trajectories and conserved quantities for \( M_s/M_h = 10^{-4}, 10^{-3}, 10^{-2} \). For inner (outer) escapes, the energy and angular momentum decrease (increase) after the initial transient for \( t < 0.5 \). Fig. 15 shows that the energy change for ensembles of orbits in the leading tail chosen as follows. The initial position is chosen to be 2 per cent of \( r_s \) outside of the X-point and the velocities are chosen to have a normal distribution in the satellite frame with a dispersion that is 2 per cent of the satellite’s circular velocity at \( r_s \). The orbits in Figs 12–14 are representative members of these ensembles.
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The magnitude of the energy change $\Delta E$ is defined as the ensemble average of $|E_{\text{min}} - E_{\text{init}}|$ where $E_{\text{init}}$ is the initial energy and $E_{\text{min}}$ is the minimum energy along the orbit. These numerical values are consistent with the predicted scaling $(M_s/M_h)^{1/3}$. Circumstance may eventually bring the ejected particle close to the satellite once again, as seen in Fig. 14. The radial extent of the annulus covered by the orbit increases only gradually with increasing satellite mass, reflecting the same weak dependence on $M_s/M_h$. In the simulations, the mass-loss and subsequent re-equilibration of the satellite potential causes small deviations in the Jacobi constant even though the satellite orbit remains circular as shown in Fig. 16. None the less, the restricted three-body dynamics explains most of the features seen in the orbit evolution.

3.2.2 Non-circular orbits

Although we still expect some of the insight gained from the restricted three-body problem to carry over to the evolution of a satellite on an eccentric orbit, this more complex situation requires direct simulation. Fig. 17 shows the tidal tails of a massive and low-mass satellite on an eccentric, $e = 0.5$, orbit. The tidal tail morphology for eccentric satellite orbits is significantly more complex than for circular satellite orbits and varies more strongly with satellite mass. In the left-hand panel of Fig. 17, the massive satellite has dramatically decelerated the leading tail, which now reaches the host halo centre and forms an inner ‘reservoir’ of ejecta. The deceleration by the satellite causes the leading tail to appear close to radial. In the right-hand panel of Fig. 17, the multiply segmented tail from the low-mass satellite is caused by two mechanisms. First, during each satellite orbit, the leading tail forms during the approach to pericentre. After pericentre, the tidal strain and the mass-loss rate diminishes resulting in a gap in the tail. Secondly, deceleration by the satellite changes the orbits of the newly disconnected leading tail, producing a distinct segment.

Fig. 18 shows the evolution of a massive satellite on an $e = 0.74$ orbit. Initially, the leading tail points directly towards the halo centre but the strong deceleration by the satellite eventually fills the inner halo with ejecta. Fig. 19 provides a finer time sampling of the evolution between pericentre and apocentre for the same simulation. Instantaneously, the morphology can be very complex and the position angle of the leading tail can vary significantly from its nearly radial average. There is little correlation between the tail location and the satellite orbit. The location of the inner ejecta, e.g. its outer turning points, is determined by the host halo potential, the time-varying satellite potential, and the satellite orbit in combination. Therefore, unlike streams from very low-mass satellites, the tail
4 OBSERVATIONAL APPLICATIONS

We have demonstrated that tail morphology depends sensitively on the satellite mass and orbit. For modest to high-mass satellites, the ejected tails have orbits that differ significantly from that of the progenitor satellite. In this section, we illustrate the observational implications of these results.

4.1 Projected satellite tail morphology

The observational implications for Milky Way streams can be summarized by projecting the tail star counts and radial velocity signatures against the sky with the observer at the centre of host halo. Fig. 20 shows Aitoff projections of number density and mean radial velocity for the massive satellite (top panels) and the low-mass satellite (bottom panels) with an $e = 0.5$ orbit (the same simulations described in Fig. 17 at the same time, $T = 5.0$). The Aitoff projection covers the entire sky, $0^\circ \leq l \leq 360^\circ$ and $-90^\circ \leq b \leq 90^\circ$, and the pixel size is $4^\circ \times 4^\circ$. The number density of the particles (left-hand panels) and the mean radial velocity (right-hand panels) are coded by colour. The contours in all the panels represent the particle number density. Velocity outliers at low number density are trimmed by setting to $\bar{v}_r = 0$ all the pixels with fewer than 10 particles. The satellites are located at $l \approx 270^\circ$ and $b \approx 0^\circ$ and move in the positive $b$ direction.

The radial velocity signatures of the massive and low-mass satellites are distinctly different. These qualitative differences are a direct consequence of the large energy and angular momentum changes of the ejecta orbits leading to the phase wrapping of the leading tail and the dramatic broadening of the trailing tail (see Section 3.2.2). This causes the lower overall mean velocity values with a more rapid angular variation around the sky. In contrast, the mean velocities of the leading and trailing tails for the low-mass satellite are smooth and slowly vary around the sky. Quite clearly, the debris from the massive satellite will not show the distinct kinematic and spatial signatures that have been exploited in recent observational campaigns.

orientation is not directly informative. However, through dynamical modelling, the location of the inner ejecta may provide constraints on combinations of satellite properties and its history, and the galaxy potential.

$^3$ A specific Milky Way model would take into account the solar position and an orbital estimate for a particular progenitor satellite. However, in this study, the satellites are chosen to be only representative of CDM predictions and, in the same vein, the galaxy centre is an intuitively simple inner galaxy viewpoint.
4.2. The effects on tidal tail radial velocity

Radial velocity - orbital longitude diagrams are frequently used to characterize large-scale kinematic features in the Milky Way. Fig. 21 shows radial velocity - orbital longitude diagrams for the effects of satellites with orbits having $e = 0.5$ for each of our three masses. We convert simulation units to Milky Way units by assuming a virial radius of 250 kpc and total mass of $10^{12}$ $M_\odot$ (Klypin, Zhao & Somerville 2002). In Fig. 21, the Sun has $R = (0.0, 0.0, 0.0)$ kpc and the Galactic plane is the $z = 0$ plane. All satellites have $R = (50.0, -7.5, 0.0)$ kpc and move in the $z$ direction. The radial velocity is measured along the satellite's orbit. The spread in $|v_r|$ increases with satellite mass, as expected from the previous discussion and the fact that the mean velocity will be an unbiased diagnostic of the satellite orbit only for very low-mass satellites. Although we have only modeled the dark matter distribution, it is likely that the $v_r$ - $l$ space distribution for stellar dark matter is similar in most cases since the internal satellite velocity dispersion plays a minor role in shaping the ejecta distribution.
Law et al. (2005) use M giants from the Two Micron All Sky Survey (Skrutskie et al. 2006) to map the position and velocity distributions of tidal debris from the Sagittarius dwarf spheroidal galaxy. Assuming that tidal tails approximately align with the satellite trajectory, the authors note that the radial velocity distribution of tidal debris suggests an oblate Milky Way halo with an axis ratio of $q = c/a = 1.25$. However, our results demonstrate that the tails do not follow the satellite orbit. In Fig. 21, we also plot satellite trajectories for three different halo flattenings to compare with the particle distributions of our simulations evolved in a spherical host halo. Following Law et al. (2005), we flatten our host halo parallel to the satellite’s motion and compute point mass satellite trajectories to compare with our simulated $v_r$–$l$ diagrams. Surprisingly, the distributions of the low-mass satellite and the tiny-mass satellite tidal tails most closely matches a $q = 0.9$ halo. The gravitational acceleration by the satellite shifts the tail location in the radial velocity distribution and this trend is degenerate with the effects of halo flattening. For instance, the location of the leading tails decelerated by a massive satellite is degenerate with the trajectories of tails in an oblate halo with no satellite deceleration. We have not attempted to model the Milky Way in sufficient detail to estimate the halo flattening including satellite deceleration. However, the degeneracy between halo flattening and the shift caused by the satellite gravitational acceleration suggests that the Law et al. (2005) conclusions may be biased and a more careful analysis including the full dynamics of the halo–satellite interaction is necessary.

### 4.3 The effects on the tidal tail phase-space distribution

Several groups have proposed phase-space-based detection diagnostics for moving groups associated with disrupted dwarf galaxy and star cluster streams. Lynden-Bell & Lynden-Bell (1995) proposed using the intrinsic correlation of moving groups’ radial energy and galactocentric radius to identify disrupted systems. The procedure is as follows. Assuming a spherical gravitational potential for the outer galaxy, one estimates the radial energy $E_r = v_r^2/2 + \Phi(r)$ and the galactocentric radius $r$ of the putative ejecta stars from observations. Then, assuming that all of the debris from a single satellite has the same orbital energy, $E$, and angular momentum, $L$, conservation of energy implies a simple linear relationship in $r^{-2}$: $E = E_L - L^2/2r^2$. Hence, linear features in the observed $E_r$–$r^2$ diagram indicate the detection of a tidal stream. Recently Belokurov et al. (2007) used this method to support the detection of stellar streams in the Sloan Digital Sky Survey.

However, as we have now seen, a massive satellite will modify the conserved quantities of the ejecta orbits and change their location in $E_r$–$r^{-2}$ space. Figs 22 and 23 show the $E_r$–$r^{-2}$ diagrams for the low-mass and tiny-mass satellite simulations on an $e = 0.5$ orbit. For clarity, we have reduced the point density by randomly sampling the simulation phase space and plot the bound particles at five different times in the upper left-hand panels. We calculate the expected linear relation from the satellite’s initial position and velocity. The bound material in low- and tiny-mass satellites lies along the predicted linear relation at all times. We plot the tail particles at three different times in the other three panels. As one can see in Fig. 22, the deviation of the tail particles from the predicted locus and the scatter in $E_r$ at fixed $r^{-2}$ for the low-mass satellite is large. Especially at late times, e.g. the bottom right-hand panel in Fig. 22, the tail nearly fills the region between the zero-velocity curve and the predicted locus. However, one can see from Fig. 23 that tail particles from the tiny-mass satellite do follow the predicted linear relation. Therefore, we conclude that the Lynden-Bell & Lynden-Bell (1995) diagnostic can only detect streams from very low-mass satellites such as globular clusters.

Motivated by the prospect of six-dimensional phase-space data from future astrometric missions, Helmi & de Zeeuw (2000) proposed to identify phase-mixed satellite debris by a cluster analysis in $(E, L, L_z)$ space. We explore the consequences of tail evolution on this approach using the same two simulations in Fig. 24 for the low-mass satellite and in Fig. 25 for the tiny-mass satellite. For simplicity, we assume that we know the orbital orientation and consider only the $E$–$L_z$ projection. The top left-hand panel shows the distribution at 0 Gyr ($T = 0$) and at 8 Gyr ($T = 4$) when scaled to the Milky Way halo in $E$–$L_z$ space. Once again, we randomly sampled the material to improve clarity. The top right-hand and bottom left-hand panels show density estimates in $E_r$–$L_z$ space for the satellite at 0 and 8 Gyr, respectively. In the bottom right-hand panels we show the density of only the tail particles at 8 Gyr. The overall position of the satellite and its tail changes little from 0 to 8 Gyr, although the shape of the distribution shifts. In both figures, there are two or more
peaks at high and low energy with respect to the satellite owing to
decelerations and accelerations of tail particles by the satellite po-
tential. Moreover, the tidal field is non-axisymmetric and this leads
to spatial correlations in the energy and angular momentum of the
least bound satellite particles, which in turn leads to the produc-
tion of several apparently disassociated phase space clumps before
disruption.

5 DISCUSSION AND SUMMARY

The observational detection of ‘S’- or ‘Z’-shaped tidal tails in glob-
ular clusters (e.g. Leon, Meylan & Combes 2000; Odenkirchen et al.
2003; Grillmair & Dionatos 2006) promises sensitive statistical tests
of the Galaxy’s gravitational potential and has renewed the quest
for streams from larger satellites. For globular clusters, i.e. very
low-mass satellites, the tidal tail morphology is easily interpreted
(Capuzzo Dolcetta, Di Matteo & Miocchi 2005; Montuori et al.
2007). However, for massive satellites, the bisymmetry that leads
to this simple morphology is broken by the interaction of the host
halo’s gravitational field and the self-gravity of the satellite itself.
We present new dynamical aspects and morphologies of tidal tails
produced in satellites of significant mass, $M_s / M_h > 0.0001$. There
are two dynamical principles that affect the tail production for mas-
sive satellites. First, the leading and trailing X-points, points where
the attractive force of the host halo and satellite are balanced at
zero velocity, do not occur at equal distances from the centre nor
do they have the same equipotential value for large-mass satellites
(see Fig. 11). Secondly, the escaped ejecta in the leading (trailing)
tail continues to be decelerated (accelerated) by the satellite’s grav-
ity leading to large offsets of the ejecta orbits from the satellite’s
original orbit (see Fig. 17). We show that this is consistent with Hill–
Jacobi theory (generalized to dark matter haloes) for satellites on
circular orbits. In particular, the effect of the satellite’s self-gravity
on the tail decreases only weakly with decreasing satellite mass,
proportional to $(M_s / M_h)^{1/3}$ (see Section 3.2.1) and, therefore,
the acceleration by the satellite after escape is important for dwarfs
and dark haloes of modest mass.

These findings have several important and useful theoretical and
observational consequences. First, for a finite mass satellite, the
morphology of the leading and trailing tails will be different owing
to the gradient in the underlying halo potential across the satellite.
In addition, the tail ejection occurs over a range of azimuth relative
to the X-point owing to the dynamical response of the originally
prograde and retrograde orbits to the tidal and non-inertial accelera-
tion. These effects should be observable in high-resolution imaging
for both dwarf spheroidal and globular clusters (see Figs 17–19).

Secondly, the radial velocity of tail particles will be displaced
from that of the satellite orbit. The magnitude of the displacement is
proportional to the satellite mass. These trends distort the ejecta
from the gravitationally bound satellite trajectory in the $v_r – l$ plane
in much the same sense as a satellite trajectory in a flattened halo (see
Fig. 21). In other words, in fitting the $v_r – l$ diagram for tidal tails to
satellite orbits of different flattenings, the satellite mass is covariant
with halo flattening, i.e. the shape parameter $q = c/a$. Therefore,
a constraint on the Milky Way halo shape using tidal streams requires
mass-dependent modelling. Finally, the acceleration of ejecta by a
massive satellite during escape spreads the velocity distribution and
obscures the signature of a well-defined ‘moving group’ in phase
space (see Figs 22–25).

Although we believe that the physical effects described in this
study are robust, our intentionally idealized simulations ignore sev-
eral possibly relevant processes. First, the dynamical friction and the
self-gravitation of the tail are ignored, although in all but the most
extreme mass satellites their effects on the tail morphology will be
negligible, since the mass in the tail is very small. Secondly, we
assume a smooth and static spherical host halo potential. In reality,
over time, as the host halo mass grows its shape may change, and
the ejecta will be perturbed by substructure. These time-dependent
effects will not affect the applicability of the dynamics described
here but will complicate the prediction of observational signatures.
Finally, we have not included the physics of a dissipational baryonic
component that may have slightly different kinematics than that of
a dark collisionless component. In spite of these shortcomings, our
study elaborates the details of satellite tidal tail production and the
dynamics that bear on the interpretation of observed streams.

As an example, Moore & Davis (1994) and Johnston et al. (1996)
find that satellite tails follow the satellite orbit for dwarf galaxies
whose mass is negligible compared to the galaxy mass. The mass of
these satellites is usually similar to or less than our tiny-mass satel-
lette. Using these simulation results, Johnston et al. (2001) devel-
oped an efficient numerical method to investigate the detectability
and interpretation of tidal debris tails. However, we have demonstr-
ated here that the gravity of the satellite for $M_s / M_h \geq 0.0001$
will change the actions of the tidal ejecta to mimic halo flattening
(see Section 4.2, Fig. 21). In addition to the spatial distribution,
the velocity distribution of the tail is affected by the satellite potential (see Section 4.3). We would like to note that (Fujii, Funato & Makino 2006) have also noticed a systematic distance offset for leading (trailing) tails inside (outside) the orbit of a satellite owing to the satellite potential. However, they did not focus on the tail morphology.

In summary, we have shown that the interplay between the satellite and the host halo results in a complex tail morphology whose amplitude scales weakly with mass. Although these findings complicate the interpretation of stellar streams and moving groups, the intrinsic mass dependence provides additional leverage on both the halo and on the progenitor satellite properties. A statistical study of these trends will further constrain the dark halo potential and the mass accretion history of the Milky Way.

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