Tidal tails of dwarf galaxies on different orbits around the Milky Way

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ABSTRACT
We present a phenomenological description of the properties of tidal tails forming around dwarf galaxies orbiting the Milky Way. For this purpose we use collisionless N-body simulations of dwarfs initially composed of a disc embedded in an NFW dark matter halo. The dwarfs are placed on seven orbits around the Milky Way like host, differing in size and eccentricity, and their evolution is followed for 10 Gyr. In addition to the well-studied morphological and dynamical transformation of the dwarf’s main body, the tidal stripping causes them to lose a substantial fraction of mass both in dark matter and in stars which form pronounced tidal tails. We focus on the properties of the stellar component of the tidal tails thus formed. We first discuss the break radii in the stellar density profile defining the transition to tidal tails as the radii where the profile becomes shallower and relate them to the classically defined tidal radii. We then calculate the relative density and velocity of the tails at a few break radii as a function of the orbital phase. Next, we measure the orientation of the tails with respect to an observer placed at the centre of the Milky Way. The tails are perpendicular to this line of sight only for a short period of time near the pericentre. For most of the time the angles between the tails and this line of sight are low, with orbit-averaged medians below 42° for all, even the almost circular orbit. The median angle is typically lower while the maximum relative density higher for more eccentric orbits. The combined effects of relative density and orientation of the tails suggest that they should be easiest to detect for dwarf galaxies soon after their pericentre passage.

Key words: galaxies: dwarf – galaxies: fundamental parameters – galaxies: kinematics and dynamics – Local Group – dark matter.

1 INTRODUCTION
Tidal tails of dwarf galaxies in the Local Group can provide important insight into the formation scenarios of the Milky Way, M31 and their satellites. According to the presently accepted theories of structure formation in the Universe, all galaxies formed by mergers and accretion of smaller objects. Tidal tails thus should be omnipresent in the vicinity of the Milky Way as witnesses of the past accretion events. As most of the dwarf galaxies were probably accreted at redshifts $z = 1–2$ they should have had enough time to produce pronounced tidal extensions as a result of their interaction with the Milky Way. It is also believed that the stellar halo of our Galaxy formed from stars lost during such processes (Johnston 1998; Bullock & Johnston 2005). The features of tidal tails depend on the properties of the progenitor as well as the host and are thus useful to constrain the Milky Way potential (Johnston et al. 1999a; Peñarrubia et al. 2006; Law & Majewski 2010; Koposov, Rix & Hogg 2010; Ibata et al. 2013).

Most of the studies of the formation of tidal tails in the Local Group to date were done in the context of tidal stripping of Galactic globular clusters (Oh, Lin & Aarseth 1992; Oh & Lin 1992; Küpper, Lane & Heggie 2012). Although smaller than dwarf galaxies in size, they are typically located much closer to the Galactic Centre than the dwarfs and therefore easier to disrupt. And indeed compelling evidence for the presence of tidal tails around globular clusters has been found with the most prominent example being the one of Palomar 5 (Odenkirchen et al. 2003).

The main reason why tidal tails of dwarf galaxies were not as yet extensively studied is probably the lack of good photometric and kinematic measurements. Although some indication of the presence of the tails was found in Ursa Minor (Martínez-Delgado et al. 2001), Carina (Muñoz et al. 2006) or Leo I (Sohn et al. 2007) and hints of stream-like overdensities have also been detected around some of the ultra-faint satellites of the Milky Way (Sand et al. 2012), the presence of tidal tails around most Local Group dwarf galaxies...
is still under debate (Fringalbovy et al. 2012; Łokas et al. 2012). A notable counter example is the Sagittarius dwarf whose tails were detected beyond any doubt (Majewski et al. 2003) and studied in detail by many authors (e.g. Johnston, Spergel & Hernquist 1995; Johnston et al. 1999b; Helmi & White 2001; Helmi 2004; Law, Johnston & Majewski 2005; Law & Majewski 2010; Łokas et al. 2010). Interestingly, streams of stars with probable tidal origin but without obvious progenitor identified have been discovered in the Local Group, e.g. the Orphan stream (Belokurov et al. 2007) or the Monoceros stream (Newberg et al. 2002). There is also compelling evidence of tidal features around dwarf galaxies and streams beyond our immediate cosmic neighbourhood (e.g. Martínez-Delgado et al. 2010, 2012; Koch et al. 2012).

Klimentowski et al. (2009a) used N-body simulations to study the properties of tidal tails forming around a dwarf galaxy interacting with a Milky Way like host. The dwarf was placed on an eccentric orbit typical of Milky Way satellites with apo- to pericentre distances \( r_{apo}/r_{peri} = 120/25 \) kpc. Contrary to earlier studies which assumed a spherical, single-component progenitor (e.g. Johnston, Choi & Guhathakurta 2002; Choi, Weinberg & Katz 2007), the dwarf galaxy was initially composed of a stellar disc embedded in a dark matter halo and was thus akin to dwarf irregular galaxies believed to be progenitors of the present-day dwarf spheroidal (dSph) galaxies according to the tidal stirring scenario (Mayer et al. 2001). Their study was the first to address the issue of the formation of tidal tails in the context of this scenario and without the assumption of the tidally stripped dwarf being spherical.

The most interesting finding of this work was the conclusion related to the orientation of the tails with respect to an observer placed near the centre of the Milky Way. It turned out that the tails are typically inclined by a rather small angle to this line of sight and therefore may not be easy to detect except for a brief period of time when the dwarf galaxy is near the pericentre of its orbit. This finding also had important implications for the mass modelling of dSph galaxies since tidal tails oriented along the line of sight tend to significantly contaminate kinematic samples used to determine masses (Klimentowski et al. 2007).

Although typical for subhaloes accreted at redshift \( z = 1–2 \), the orbit considered by Klimentowski et al. (2009a) was only one of the whole spectrum of orbits found in simulations of the Local Group (Diemand, Kuhlen & Madau 2007; Klimentowski et al. 2010). Here we extend the work of Klimentowski et al. (2009a) to include orbits of different size and eccentricity while still working within the context of the tidal stirring model, i.e. assuming realistic progenitor discy dwarfs. Our initial conditions also differ slightly in the way we model the dwarf and the host galaxy.

The article is organized as follows. In Section 2 we briefly describe the simulations used in this work. Section 3 is devoted to the description of the stellar density profiles of the simulated dwarfs and in their immediate vicinity with the purpose of determining the radius of transition between the dwarf’s main body and the tidal tails. In Section 4 we discuss the density and kinematics of the tails as a function of their orbital phase and in Section 5 we look at the orientation of the tails with respect to the line of sight of an observer placed near the centre of the Milky Way. The discussion follows in Section 6.

### 2 THE SIMULATIONS

The collisionless N-body simulations we use here were presented in detail in Kazantzidis et al. (2011) and Łokas, Kazantzidis & Mayer (2011). These works focused on the study of the formation of dSph galaxies via tidal stirring of rotationally supported dwarfs in the vicinity of Milky Way sized hosts.

In this work we use a single model of a dwarf galaxy constructed numerically using the method of Widrow & Dubinski (2005). The dwarf is composed of an exponential stellar disc embedded in a cuspy, cosmologically motivated Navarro, Frenk & White (1997, hereafter NFW) dark matter halo. The halo had a virial mass of \( M_h = 10^9 \) \( M_\odot \) and a concentration parameter \( c = 20 \). The disc mass, \( m_d \), was specified as a fraction of 0.02 of the halo mass. The disc radial scale length was \( r_d = 0.41 \) kpc (Mo, Mao & White 1998) and the disc thickness was determined by the thickness parameter \( \epsilon_d/r_d = 0.2 \), where \( \epsilon_d \) denotes the vertical scale height of the disc. The dwarf galaxy model contained \( N_h = 10^6 \) dark matter particles and \( N_d = 1.2 \times 10^8 \) disc particles. The gravitational softening was chosen to be \( \epsilon_h = 60 \) pc and \( \epsilon_d = 15 \) pc for the two components, respectively. The initial density profiles of stars and dark matter in the dwarf measured in spherical shells are shown in Fig. 1.

The Milky Way model was constructed as a live realization of the MWb model of Widrow & Dubinski (2005) with an exponential stellar disc of mass \( M_d = 3.53 \times 10^9 \) \( M_\odot \), a bulge of mass \( M_B = 1.18 \times 10^{10} \) \( M_\odot \) and an NFW dark matter halo of mass \( M_h = 7.35 \times 10^{11} \) \( M_\odot \). Our model of the Milky Way had \( N_d = 10^6 \) particles in the disc, \( N_h = 5 \times 10^8 \) in the bulge and \( N_{hi} = 2 \times 10^8 \) in the dark matter halo. The adopted gravitational softenings were \( \epsilon_d = 50 \) pc, \( \epsilon_B = 50 \) pc and \( \epsilon_H = 2 \) kpc, respectively.

The dwarf galaxy model was placed on seven different orbits O1–O7 (see Table 1) around the primary galaxy. The orientation of the internal angular momentum of the dwarf with respect to the orbital angular momentum was mildly prograde and equal to

![Figure 1. Spherically averaged density profiles of stars (solid line) and dark matter (dashed line) of the dwarf galaxy in the initial configuration.](https://example.com/figure1)

| Orbit | \( r_{apo} \) (kpc) | \( r_{peri} \) (kpc) | \( r_{apo}/r_{peri} \) | \( T_{orb} \) (Gyr) | \( t_s \) (Gyr) | \( n_{peri} \) | \( R_{rad} \) (kpc) | Colour |
|-------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|--------|
| O1    | 125             | 25              | 5               | 2.09            | 8.35            | 5               | 12.7            | Green  |
| O2    | 85              | 17              | 5               | 1.28            | 8.95            | 8               | 10.7            | Red    |
| O3    | 250             | 50              | 5               | 5.40            | 5.40            | 2               | 34.2            | Blue   |
| O4    | 125             | 12.5            | 10              | 1.81            | 9.05            | 6               | 11.0            | Orange |
| O5    | 125             | 50              | 2.5             | 2.50            | 10.00           | 4               | 11.7            | Purple |
| O6    | 80              | 50              | 1.6             | 1.70            | 8.50            | 6               | 7.6             | Brown  |
| O7    | 250             | 12.5            | 20              | 4.55            | 9.10            | 2               | 21.9            | Black  |

Table 1. Orbital parameters of the simulated dwarfs.
In all simulations, the dwarf was initially placed at the apocentre of the orbit and the evolution was followed for 10 Gyr using the multisteping, parallel, tree $N$-body code PKDGRAV (Stadel 2001).

The orbits were chosen so as to probe a variety of sizes and eccentricities and their effect on the tidal tails formed during the evolution. The orbital apocentres, $r_{\text{apo}}$, and pericentres, $r_{\text{peri}}$, are listed in the second and third columns of Table 1. In the first three orbits O1–O3 only the size was varied while keeping the ratio $r_{\text{apo}}/r_{\text{peri}}$ (fourth column of Table 1) constant and equal to 5, a value characteristic of subhaloes in cosmological environments of the size of the Milky Way halo (Diemand et al. 2007). The sizes of orbits O1–O3 bracket those typically found for subhaloes in the Local Group that survived until the present time (Klimentowski et al. 2010). In particular, the tight orbit O2 is similar to the best estimates of the orbit of the Sagittarius dwarf (Law et al. 2005; Łokas et al. 2010) while the extended orbit O3 is close to the one recently estimated for the Large Magellanic Cloud (Besla et al. 2007). The intermediate orbit O1 can be considered as a typical orbit of a subhalo falling in at redshift $z = 1–2$. Orbits O4–O7 vary in size and eccentricity so that both smaller and larger eccentricities are covered.

The orbital times corresponding to all orbits are listed in the fifth column of Table 1. In the sixth column we provide the times of the last apocentre and in the seventh the number of pericentre passages the dwarf experienced during the 10 Gyr of evolution. The last column gives the colour with which the results for a given orbit will be shown throughout the paper. The left-hand panels of Fig. 2 show the seven orbits considered in this work projected on to the initial orbital plane. Note that the orbits are not exactly planar because the potential of the Milky Way, in which the dwarfs evolve, is not exactly spherical. The departures from the sphericity, introduced by the presence of the Milky Way disc inclined by $45^\circ$ to the initial orbital planes of the dwarfs, make the orbits deviate from these initial planes. This is especially the case for orbit O2 which has a rather small pericentre and orbital time so that at the end of the evolution the departures are quite pronounced.

### 3 THE BREAK RADIi

The detailed picture of the evolution of a dwarf galaxy on an orbit around the Milky Way has been presented in a few earlier works (e.g., Klimentowski et al. 2009b; Kazantzidis et al. 2011; Łokas et al. 2011) which focused on the properties of the dwarf’s main body. It has been demonstrated that as the dwarf proceeds on its orbit, its stellar component transforms morphologically from a disc to a bar and then a spheroid while the ordered stellar motions (the initial rotation) become more and more random. On tight enough orbits and after long enough times a spheroidal galaxy is formed. This process is accompanied by strong mass loss, in both the stellar and dark component. The material lost by the dwarf forms pronounced tidal tails on both sides of the dwarf: the leading tail, travelling faster that the dwarf, and the trailing tail which moves slower. The tails do not follow exactly the dwarf’s orbit but rather move on their own orbits of different energy around the Milky Way.

In this section we look at the scales of transition between the main body of the dwarf and its tidal tails. This transition is best quantified by measuring density profiles of the dwarf galaxy. The density profile, in both stars and dark matter, rather than steepening all the way to infinity, as is characteristic of systems unaffected by tides, steepens only out to a certain scale and then flattens. As will be discussed below, at maximum steepness the slope of the stellar...
density profile is close to $R^{-6}$ at all times, while at the outer radii it flattens to about $R^{-2}$. Let us therefore define the scale of transition as a radius where the slope becomes less and less negative and crosses the value of $R^{-4}$. In the following we will refer to this scale length of transition as the break radius.

In addition, the density profiles show a characteristic variation in time. Soon after the pericentre passage the steepest occurs at the smallest radius and the flattened profile at larger radii has a higher level of density. This happens when most of the material is ejected from the dwarf by tidal forces which are strongest at the pericentre. Later on, however, the dwarf does not stay truncated at the same scale but expands so that as the dwarf travels from the peri- to the apocentre the break radius occurs at a larger and larger distance from the centre of the dwarf until, after the next pericentre, a new strong steepest occurs and new material is fed into the tails. The increase of the break radius is accompanied by decrease in the density of material outside, in the tidal tails.

Fig. 3 shows the density profiles of stars and dark matter (solid and dashed lines, respectively) measured in spherical shells around the dwarf galaxy centre. In the right-hand panels we plot the density profiles at the last apocentre on a given orbit (except for O3 where the last output is used instead because there are too few apocentres), while in the left-hand panel we show density profiles at the preceding pericentre. The shapes of the density profiles at these two instances are clearly different. At apocentres a clear break radius and the transition to the tidal tails are seen. At pericentres no such clear transition is visible; there is rather a smooth transition from the steeper to the shallower profile. The reason for this behaviour is that the material ejected at the previous pericentre has already travelled away from the dwarf and a new ejection has not yet taken place.

We illustrate this behaviour further by plotting in Fig. 4 the break radii for dwarfs on all orbits as a function of time (solid lines). The evolution of the break radii shows a characteristic pattern: as the dwarf galaxy expands after the pericentre passage the break radius increases until well after the apocentre. As the dwarf approaches the next pericentre the stellar distribution is stretched and the break radius increases suddenly which manifests itself in peaks of break radii right after the pericentre in Fig. 4. The peaks are most pronounced and occur after all pericentre passages on orbits O2 and O4 which have the smallest pericentres. Soon after the pericentre the stellar density is trimmed again and the break radius drops to its next smallest value.

The break radii discussed here must obviously be related to the radius commonly referred to as the tidal radius. For a satellite moving on a circular orbit, the tidal radius may be approximated as a Jacobi or Roche radius defined as the last closed zero-velocity surface surrounding the satellite (Binney & Tremaine 2008, section 8.3). However, in the general case, also applicable to most dwarf galaxies orbiting the Milky Way, the orbits are not circular and there is no reference frame in which the potential experienced by the stars in the dwarf is stationary. In these cases no analogue of the Jacobi radius exists. A different approach to deriving the tidal radius was proposed by King (1962) who argued that the limit can be set by finding a radius, on the line joining the host and the satellite, where the acceleration of a star of the satellite vanishes. Read et al. (2006) generalized this derivation to take into account the type of orbit of the star within the satellite. Their formula (18) can be rewritten as

$$R_t = r \left( \frac{M_s}{M_g} \right)^{1/3} \frac{1}{\sqrt{1 + 2(r/A) + \alpha^2 + \alpha}}^{2/3}$$  (1)

Figure 3. Density profiles of the stellar component (solid lines) and dark matter (dashed lines) of dwarf galaxies at the last apocentre of the orbit (right panels) and the preceding pericentre (left panels). The times of these events are given in the upper right corner of each panel. Vertical dotted lines indicate break radii.
where \( R \) is the distance measured from the dwarf's centre, \( r \) is the distance between the centre of the Milky Way and the centre of the dwarf, \( M_1 \) and \( M_2 \) are the masses of the satellite and the host galaxy and \( \alpha \) describes the type of the star's orbit within the satellite, so that \( \alpha = 1 \), \( 0 \) and \(-1\), respectively, for prograde, radial and retrograde orbits. The formula is strictly valid only for point-mass potentials of the satellite and the host so that the orbit is Keplerian and \( \Delta = 2r_{apo}r_{peri}/(r_{apo} + r_{peri}) \). Note that after setting \( \alpha = 0 \) and \( r = r_{peri} \), formula (1) reduces to the well-known King (1962) prescription for the tidal radius

\[
R_t = r_{peri} \left[ \frac{M_1}{M_2(3 + e)} \right]^{1/3}
\]

where \( e = (r_{apo} - r_{peri})/(r_{apo} + r_{peri}) \).

King (1962) argued that once the satellite is trimmed down to this smallest tidal radius at the pericentre it will preserve this shape also in the other parts of the orbit. As shown in Fig. 4, this is not, however, the case for our dwarfs: the break radii change with the position of the dwarf on the orbit. Instead of the simple formula (2) we thus used the more general expression (1) adopting as the satellite mass the mass contained within the tidal radius, \( M_t(R_t) \) and as the Milky Way mass the mass within the current distance of the dwarf \( M_g(r) \). Given the orbits considered here the only important dependence on the distance in \( M_g \) is due to the NFW-like distribution of the dark mass in the Milky Way halo thus the disc and bulge are included as point masses. With these assumptions, equation (1) provides an implicit formula for \( R_t \), which can be solved numerically to arbitrary accuracy for any \( \alpha \). Note that replacing \( r_{peri} \) by \( r \) in equation (2) does not lead to the correct prescription for the tidal radius and formula (1) should be used instead.

The results of this semi-analytic procedure for the calculation of the tidal radius are shown as dashed lines in Fig. 4. Only the curves for the \( \alpha = 0 \) are shown, since those agree best with the values of the break radii determined from the simulations in terms of both the maximum and minimum values. We have also considered \( \alpha = 1 \) and an intermediate value \( \alpha = 0.5 \) (see below) but they lead to systematically lower predictions. The break radii of the simulated dwarfs are always delayed with respect to the instantaneous tidal radii predicted by the formula, probably because of the time the satellite needs to respond dynamically to the tidal forces exerted by the host galaxy at earlier times. Thus, the minimum of the measured break radius occurs some time after the pericentre and then the break radius monotonically increases until it reaches a plateau at the level close to the maximum tidal radius predicted by formula (1) at apocentres. After that the transition to the tidal tails in the outer density profile moves to even larger radii leading to even higher values of the break radii at and immediately after the pericentre while the predicted values already reach another minimum.

Thus the break radii of the simulated dwarfs are shifted in time with respect to the predicted tidal ones by a period the dwarf needs to dynamically respond to the tidal forces from the host. The global trend of break radii decreasing over large time-scales (of at least one orbital time), due to the mass loss of the dwarf, is however seen in both predictions and direct measurements. Both also display the clear dependence on the eccentricity of the orbit: the difference between the maximum and minimum break radius over one full orbit is significantly larger for eccentric orbits than more circular ones. In particular, the almost circular orbit O6 shows very little variation in break radii over orbital time.

It is perhaps surprising that a simple formula (1) reproduces reasonably well the general behaviour of the break radii. We have verified that the prescriptions for the tidal radius taking into account the dependence of slope of the host galaxy’s mass distribution on radius do not improve the agreement. As already mentioned, we also find the agreement to be best for \( \alpha = 0 \) which corresponds to the radial orbits of the stars in the dwarf galaxy. Although the stellar motions are initially mildly prograde with respect to the orbits (the initial discs are inclined by 45° to the orbital plane), so that \( \alpha = 1 \) or an intermediate value \( \alpha = 0.5 \) would seem more appropriate, in most cases after the first pericentre passage a bar is formed which
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4 THE DENSITY AND KINEMATICS OF THE TAILS

In the following analysis of the properties of the tidal tails we will assume that they can be reliably measured at \( R > R_{\text{tail}} \) where \( R_{\text{tail}} \) is the maximum value of the break radius occurring near the second pericentre. The values of \( R_{\text{tail}} \) found in this way are listed in the eighth column of Table 1. The adopted \( R_{\text{tail}} \) will be different for each orbit, but kept constant in time. Since the maximum break radius decreases in subsequent pericentres, this means that \( R_{\text{tail}} \) is always significantly larger than the instantaneous break radius.

One of the basic properties that can affect the modelling of dSph galaxies and also possibilities of detection of tidal tails around them is the density of stars in the tails. We measured this density as a function of time by counting stars within a shell of radii \((R_{\text{tail}}, R_{\text{tail}} + \Delta R)\) where we adopt \( \Delta R = 1 \) kpc except for the case O3 where we take a thicker shell of \( \Delta R = 6 \) kpc because the tails are very weak in this case. These choices guarantee that in all outputs (after the first pericentre) we have at least 10 stars in the shell and the measurements are meaningful. Since the volume of the shell is therefore different for each orbit, to facilitate comparison between different orbits we normalize the measurements of density to the lowest value found near the second pericentre, where the tails in all cases are already well formed (note that the second pericentre is also the last for orbits O3 and O7).

The relative density calculated in this way is shown in Fig. 6. The evolution of the density shows a characteristic pattern which is preserved at all times and for all orbits: it has a minimum at or just before pericentre, and a maximum after the pericentre passage but before the apocentre is reached. The density at the maximum is between 10 and a few hundred times larger than at the minimum and this factor depends strongly on the orbit. It is smallest for the most circular orbit O6 and among the largest for the most eccentric one O7. In addition, the maximum occurs at a smaller fraction of the orbital time after the pericentre passage for more eccentric orbits like O7; in this case the density in the tails grows steeply in time and then decreases more slowly towards the next pericentre. This behaviour is obviously due to stronger mass ejection during pericentre passage on eccentric orbits where the dwarf is tidally shocked. Interestingly, the density of the tails changes significantly (by a factor of 10) over orbital time even for the most circular orbit O6. Here, however, the phases of increasing and decreasing density last for a comparable time.
It is also interesting to measure the slope of the stellar density distribution near $R_{\text{tail}}$. The values of this slope are plotted in Fig. 5 as dashed lines. It turns out to be remarkably close to $-2$ (marked as one of the thin horizontal lines in each panel of the figure) and rather constant as a function of time (except for pericentre passages), but also uniform between orbits. This value is a direct consequence of the density of the stars being constant along the tail. The tails are thus well approximated by cylinders of constant density. When such density distributions are probed in spherical shells the resulting slope is $-2$ as we find by direct measurement. The measurements are a little more noisy for orbits O4 and O6 where debris from multiple pericentre passages overlap.

The intuitive picture of the tidal tails with the leading tail preceding the dwarf on the orbit and the trailing tail travelling behind would suggest that viewed from the centre of the dwarf galaxy, the stars in the tails should always recede. It is worthwhile to verify this statement by directly measuring the radial velocities of the tails within shells $(R_{\text{tail}}, R_{\text{tail}} + \Delta R)$ as before. We define positive velocities as those receding from the dwarf, and negative those approaching the dwarf. The results of the measurements (using the same selection of stars as for the determination of density) are shown in Fig. 7.
It turns out that the stars at $R_{\text{tail}}$ indeed move away from the dwarf for most of the time on all orbits, but they do so at all times only for the least eccentric orbits O5 and O6. For other orbits there are periods right after the pericentre passage when the stars in the tails stop with respect to the dwarf or even approach it (negative velocities). These dips of velocity are most pronounced for the most eccentric orbits O7 (after the second pericentre) and O4 (after the second and third pericentre), but are also well visible for the less eccentric orbits O1–O3. Note that the strong oscillations of velocity at later pericentres in orbits O1, O2 and O4 are due to the contribution from the debris lost much earlier. The stars in these debris would have similar properties as the stars lost recently and thus would be undistinguishable for observers. Therefore, the velocity pattern discussed above may not be observable if there are many wraps of debris lost by a given dwarf.

The interpretation of these negative velocities becomes clear once we consider the dynamics of the tails in the vicinity of the dwarf. The material in the leading tail moves faster than the dwarf and thus it reaches its pericentre sooner than the dwarf’s centre. The opposite is true for the trailing tail: it moves slower on its orbit and reaches the pericentre later. For very eccentric orbits, at the time when the dwarf has just passed the pericentre, the leading tail is already after the pericentre passage and its velocity is lower than the dwarf’s while the trailing tail is just reaching the pericentre and its velocity is larger than the dwarf’s. Thus the stars near $R_{\text{tail}}$ in both tails approach the dwarf.

5 THE ORIENTATION OF THE TAILS

Another essential factor affecting the modelling of dwarf galaxies and the possibility of studying their tidally stripped debris is the orientation of the tails with respect to an observer located near the centre of the host galaxy. Here we assume that the observer is placed exactly at the centre of the Milky Way since the Sun’s position’s offset with respect to it is small in comparison with the distances of most dwarf galaxies orbiting the Galaxy.

The stellar component of the dwarf galaxy and its tidal tails in the immediate vicinity (up to $R = 10$ kpc) are shown (projected on to the initial orbital plane) for different orbits in the right-hand panels of Fig. 2. The outputs pictured were chosen as those when the last maximum of the tails density occurs (see Fig. 6) and the time values are given in each panel. The dashed black line in each panel indicates the direction towards the Milky Way at this instant of evolution. The corresponding positions of the dwarf on the orbit at these times are marked as coloured dots in the left-hand panels of Fig. 2 showing the orbits.

In Fig. 8 we plot the angle between the tails and the direction to the centre of the Milky Way as a function of time. The line of the tails was determined by selecting as before stars in shells ($R_{\text{tail}}$, $R_{\text{tail}} + \Delta R$) and finding the major axis of their distribution from the tensor of inertia. In calculating the angle we always consider the tail closer to the direction towards the Milky Way at this instant of evolution. The corresponding positions of the dwarf on the orbit at these times are marked as coloured dots in the left-hand panels of Fig. 2 showing the orbits.

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The evolution of the orientation of the tails in time shows an interesting regularity: for all orbits the highest values of the angle are found near the pericentre. These highest values are close to 90° for eccentric orbits which means that the tails can be perpendicular to our line of sight only for a very short period of time. For the most circular orbits O6 and O5, these high angles are never reached. In these two cases the tails can be observed at most at about 50° and 70°, respectively. For most of the time, however, the tails would be observed at much smaller angles. In particular, at apocentres where the dwarfs spend most of the time, the angles are very close to zero (except for the most circular orbit O6 where they are a little larger), i.e. the tails are oriented almost exactly along the line of sight.

The picture is somewhat less clear for orbits O4 and O7 after the second pericentre. The noisy measurements at these times are due to the fact that for these very eccentric orbits the material lost at earlier pericentre passages and the tails formed after the latest pericentre are close in terms of radial direction. On the other hand, the noisy measurement at later stages of orbit O2 are due to the
tightness of the orbit (the newly formed tails are very short and the dwarf passes the previously lost debris a few times).

The probability of observing the tails at a given angle can be illustrated by plotting histograms of the number of occurrences of a given orientation as a function of the measured angle, as we do in Fig. 9. For each orbit we included measurements for the available number of full orbits between the first and the last pericentre (or a single orbit slightly shifted forward in time for orbits O3 and O7 where no measurements are available immediately after the first pericentre). The histograms were then normalized to unity. It is clear that the most probable angle of tidal tail orientation is below or very close to 20° for all orbits, except the most circular orbit O6, where it is below 40°. In addition, all orbits have a very weakly populated tail of the distribution at large angles (orbit O6 has no such tail at all).

As in the case of the velocity of the tails, this behaviour can be understood based on the dynamics of the tails as they travel along the orbit. As already discussed by Klimentowski et al. (2009a), after the pericentre passage most of the stars newly stripped from the dwarf remain close to the dwarf’s main body, but travel on their own orbits. As they approach the apocentre of the orbit, the leading tail slows down earlier than the trailing tail and the orientation of the tails becomes more aligned with the direction towards the centre of the Milky Way. The opposite is true on the way from the apocentre to the pericentre of the orbit: the tails are stretched along the orbit and their orientation becomes more perpendicular to the direction towards the Milky Way.

6 DISCUSSION

We have studied the properties of tidal tails forming around dwarf galaxies orbiting a Milky Way like host. By measuring the density profiles of the stellar components of the dwarfs we have shown that the dwarf galaxies are not truncated at tidal radii imposed at pericentres but rather expand on their way from the peri- to the apocentre. The transition to the tails occurs later than predicted by the formulae for the tidal radius. Our conclusions concerning the break radii and their relation to the tidal radii agree with the recent findings of Webb et al. (2013) for globular clusters.

The process of mass loss is not instantaneous and does not occur only at the pericentre, even for most eccentric orbits. Instead, the lost material is fed into the tails gradually and the maximum density of the tails is reached a substantial fraction of orbital time after the pericentre passage. The shape of the stellar density profile is similar at all orbital phases and all orbits: the outer profile of the dwarf’s main body follows an $R^{-6}$ law for most of the time, while the density distribution in the tails is well approximated by $R^{-2}$, a slope consistent with the debris having constant density along the tail.

Fig. 10 summarizes our results in terms of the dependence of the two crucial quantities on the eccentricity of the dwarf’s orbit around the host. In the upper panel of the figure we show the median of the angle between the tidal tails of the dwarf and the direction to the centre of the Milky Way, measured from the distributions shown in Fig. 9. The coloured dots, marked with the orbit symbol, are plotted as a function of $r_{apo}/r_{peri}$. We can see the clear trend of decreasing median angles indicated by points corresponding to orbits O6, O5, O1, O4 and O7 as we go towards the increasing eccentricity. The range encompassed by the three orbits of the same eccentricity, $r_{apo}/r_{peri} = 9$, namely O2, O1 and O3, may be considered as a measure of the scatter for this angle–eccentricity relation due to different sizes of the orbits. The fact that the median angle is significantly lower for O3 and higher for O2 in comparison to O1 is related...
The median angle between the dwarf galaxy’s tidal tails and the direction towards the Milky Way’s centre (upper panel) and the maximum density of the tails near the third apocentre with respect to the minimum near the second pericentre (lower panel) as a function of the orbit’s eccentricity $r_{apo}$/peri.

Our results also emphasize the possible issues concerning the dynamical modelling of dSph galaxies. Such modelling relies on the use of the samples of stellar velocities and can be trusted only in the case where most of the velocities are indeed those of the stars still bound to the dwarf as only those are true tracers of the underlying gravitational potential. As discussed thoroughly by Klimenzowski et al. (2007), when the dwarf’s tidal tails are oriented along the line of sight the contamination of the kinematic samples can be particularly high leading to overestimates of the mass and/or biases in the inferred density distributions and orbital properties. We have shown that this will almost always be the case as dwarfs spend most of the time near apocentres of their orbits and in addition this is also where the density of the tails is large. A particularly dangerous orbital stage from the point of view of contamination is when the dwarf galaxy is on its way towards the apocentre, because this is when the density of the tails reaches its maximum.

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