Tidal debris of dwarf spheroidals as a probe of structure formation models

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ABSTRACT

Recent observations suggest that Carina and other nearby dwarf spheroidal galaxies (dSphs) are surrounded by unbound stars tidally stripped by the Milky Way. We run high-resolution N-Body simulations of dwarf galaxies orbiting within the Milky Way halo to determine if such observations can be explained with dark matter potentials as those implied by current structure formation models. We show that tidal forces acting on dwarfs with constant density cores or with cuspy profiles having a low concentration parameter ($c < 5$) lead to flat outer stellar density profiles like that of Carina for a variety of orbital configurations. On the contrary, it is more difficult to remove stars from cuspy dark matter halos with concentrations as high as predicted by CDM models at the mass scale of dwarf galaxies ($c > \sim 10$) and the data can only be reproduced assuming nearly radial orbits. Our simulations show that Carina is losing mass at a fractional rate $<0.1\mathrm{Gyr}^{-1}$ and its mass-to-light ratio could be inflated by at most a factor of 2 due to unbound stars projected along the line of sight. We follow the evolution of the tidal debris within a triaxial clumpy cold dark matter Milky Way halo which causes differential precession and small scale heating of the stellar streams. This renders their use as a dynamical tracer of the Galactic potential practically useless, but does provide a novel test of the nature of the dark matter. Models with warm dark matter (WDM) or collisional fluid dark matter (FDM) produce dwarf halos with lower central densities than CDM and would be consistent with the observed tidal tails even for orbits with eccentricsities as low as indicated by current data on nearby dwarf spheroidals. Galactic halos in FDM are smooth and spherical and would be favored by the detection of cold coherent streams such as that associated with the Sagittarius dwarf spheroidal.

Key words: galaxies: Local Group — galaxies: dwarfs — galaxies: evolution — galaxies: interactions — cosmology: dark matter — methods: N-Body simulations

1 INTRODUCTION

In hierarchical models of structure formation the first dark matter clumps that eventually host luminous galaxies have masses comparable to the smallest dwarf galaxies in the Local Group (Haiman, Thoul & Loeb 1996, Haiman, Rees & Loeb 1996, Tegmark et al. 1997). In these models dwarf galaxies represent the cornerstones of galaxy formation; observations of dwarf galaxies should thus provide fundamental tests to our current understanding of how structure formation has proceeded in the Universe. Some of the properties of dwarf galaxy populations in the Local Group and other nearby groups (Grebel et al. 2001) can be understood within the hierarchical clustering scenario; the morphology-density relation, namely the fact that dwarf spheroidals (dSphs) are clustered around the dominant galaxies in the groups while dIrrs are found at much larger distances from them (Mateo 1998; Grebel 2000) likely reflects the continuous transformation of dIrrs into dSphs as they fall into the overdensity of the group and are stirred by the tidal field of the primary galaxies (Mayer et al. 2001a,b). On the other hand, the currently popular incarnations of hierarchical scenarios, namely cold dark matter models, are challenged by the apparent dearth of small satellites below $V_c = 30\mathrm{km/s}$ (Moore et al. 1999; Klypin et al. 1999) and by the rotation curves of...
Dwarf spheroidal galaxies in the Local Group are the faintest galaxies known in the Universe to date (Cote et al. 1997; Lake & Skillman 1991; de Blok & McGaugh 1997, de Blok et al. 2001; McGaugh, Rubin & de Blok 2001; Van den Bosch et al. 2001) These problems have recently motivated the exploration of alternative models, such as self-interacting dark matter (SIDM, Spergel & Steinhardt 2000, Moore et al. 2000, Yoshida et al. 2000a,b; Firmani et al. 2000a,b; Hogan et al.), warm-dark matter (WDM) (Bode et al. 2001; Dalcanton & Hogan 2001; Avila-Reese et al. 2000a,b; Hogan et al.), constant density cores instead of the predicted steep cusps (Dubinski et al. 1996; Mihos et al. 1998; Springel & White 1999). Observational evidence of streams associated with tidally stripped dwarfs, such as Sagittarius, is constantly accumulating in the stellar halo of the Milky Way (Helmi et al. 2000, 2001; Martinez-Delgado et al. 2000, Ibata et al. 2001; Dohm-Palmer et al. 2001; Vivas et al. 2001) and, more recently, even around the nearby Andromeda galaxy (Ibata et al. 2001b). For more distant dSphs the flattening of the star counts in the vicinity of the nominal tidal radius (Irwin & Hatzidimitriou 1995) has been often interpreted as a signature of the presence of tidal tails (Johnston et al. 1999). However, some authors have argued that such peculiar profiles indicate that the dwarfs are not bound and thus no dark matter would be needed to explain the large velocity dispersions (Kuhn & Miller 1989; Klessen & Kroupa 1995). Recently, observations that take advantage of wide field photometry have confirmed the flattening of the star counts out to larger radii in Carina (Majewski et al. 2000; Kuhn et al. 1999), while the cases of Draco (Piatek et al. 2001) and Ursa Minor (Martinez-Delgado et al. 2001) are still controversial. Majewski et al. claim on the basis of the observed extra-tidal extension, that Carina must have experienced a very large mass loss rate, losing more than 90% of its initial mass in 10 Gyr due to stripping by the Milky Way’s tides.

The size and mass of unbound structures originating from the galaxies must be determined by both the typical densities of the latter (including dark matter) and the scale-length of their stellar components. Very dense systems, or systems with stellar components whose size is such that they lie well inside the tidal radius, will be harder to strip (Moore 1996). In CDM models dark matter halos have cuspy profiles with inner slopes $\sim r^{-1}$ towards the characteristic scale radius and $r_{200}$ is the tidal radius) can vary considerably (Bullock et al. 2000); the higher is the concentration the steeper is the rise of the rotation curve and hence the local escape speed will be also higher.

It has been shown that there is enough freedom in the structural parameters allowed by CDM for large galaxies in the process of merging to form massive tails as observed (Dubinski et al. 1996; Mihos et al. 1998; Springel & White 1999). However, these conclusions cannot be trivially extended to smaller mass scales because the typical concentration of halos (and thus their central density) increases substantially with decreasing mass in CDM cosmogonies. Moreover, the choice of the orbital parameters of the interacting systems also plays a role by defining both the typical intensity and the time dependence of the external tidal forces; for the dwarf satellites of the Milky Way and M31, we have distances and some information on the orbits themselves (Mateo 1998), which allows us to constrain the parameter space better than in the case of more remote binary systems. In addition, the subsequent evolution of the material stripped from dwarf satellites can provide useful information on the potential of the Milky Way and M31; in fact, the orbits that the tidal debris will follow will reflect the underlying mass distribution.

In order to explore the role of tidal effects on stellar systems embedded in halos analogous to those forming in cold dark matter models, we have carried out several high-resolution N-Body simulations of dwarf galaxies interacting with the external potential of the Milky Way. The simulations were performed with PKDGRAV, a fast, parallel binary treecode (Dikaiakos & Stadel 1996; Stadel, Quinn & Wadsley 2002). The paper is organized as follows: in the next section we will provide a description of the models used for the dwarf galaxies, section 3 will be devoted to the results of the simulation, and finally we will discuss and summarize our findings.

2 INITIAL CONDITIONS

Many previous studies that investigated the tidal disruption of dSphs (Johnston et al. 1997; Ibata et al. 1998; Klessen & Kroupa 1998; Helmi & White 1999) employed spherical King models to represent their mass distribution and placed them on mostly circular orbits in the potential of the primary halo. The structure and orbits of the galaxies were thus detached from the predictions of structure formation models. We use more sophisticated models of dwarf satellites, whose halo masses, sizes and density profiles are consistent with those of objects already in place at z = 1 in hierarchical cosmologies (White & Frenk 1991), the dSphs being at least as old. The initial dwarf models are placed on bound orbits in the Milky Way halo, which is modeled by the external potential of an isothermal sphere with mass $M_{\text{prim}} = \sim 3 \times 10^{12} M_\odot$, circular velocity $V_{\text{prim}} = 220$ km/s, virial radius $R_{\text{prim}} = 400$ kpc and core radius of 4 kpc (see Mayer et al. 2001b for more details). The dwarfs are rotationally supported, exponential disks embedded in truncated isothermal halos with a core or within NFW halos (Hernquist 1993; Springel & White 1999) and resemble observed dIrrs. Disks and halos are sampled by $5 \times 10^3$ and $3.5 \times 10^5$ particles, respectively. After several orbits the dwarfs will be transformed into dSphs and will satisfy the morphology-density relation (Mayer et al. 2001a,b).

The halos are exponentially truncated at $r_2 = R_{200}$, where $R_{200}$ is their virial radius (i.e. the radius encompassing an overdensity equivalent to 200 times the average density of the Universe). In particular, here we consider models
of low-surface brightness (LSB) dIrrs because these are the likely progenitors of dSphs (Mayer et al. 2001a,b). The models with truncated isothermal halos have a constant density core with radius $r_c$ such that $r_c = 0.035 r_s$. Models with NFW halos are characterized by the concentration $c = r_c/r_s$, where $r_s$ is the characteristic scale length of the halo, namely the radius at which the slope of the profile changes from $r^{-2}$ to $r^{-3}$ (Navarro et al. 1996, 1997); we consider models with either $c = 4$ or $c = 7$. The satellites span a range in initial circular velocities, from $V_c = 20$ km/s to $V_c = 75$ km/s; across such a mass range the typical concentration of halos in LCDM models is $c \geq 9$ (Eke et al. 2001). The surface density of the disks are kept fixed (except in model LIs3 and in the model described in section 4) and corresponds to a central (B band) surface brightness $\mu_B \sim 23.5$ mag arcsec$^{-2}$, assuming a stellar mass-to-light ratio $(M/L_B)_{*} = 2$ (Bottinella 1996; de Blok & McGaugh 1997). Models of different masses are simply rescaled using the cosmological scaling between virial mass, virial radius and circular velocity (Mo et al. 1998). The details of the procedure used to assign the structural parameters of the halo and disks of the satellites are explained in Mayer et al. (2001) and Mayer et al. (2001b).

The models employed in this paper include a major improvement in that the scale length of the disks, $r_h$, instead of being a free parameter, is determined by the structural parameters of the dark halo, as in current galaxy formation models. In the latter models it is assumed that the specific angular momentum of the gas, bound to the dark halo, that cools and eventually fall towards the center forming the stellar disk is initially equal to that of the halo and is conserved during the infall (Fall & Efstathiou 1980; Mo et al. 1998).

Figure 1. Rotation curves of initial model galaxies for the smallest mass scale considered ($V_c = 25$ km/s, $M_{sat} = 3 \times 10^{-4} M_{prim}$). The other mass models are simply rescaled versions of those shown here, as explained in the text. In the panels the spin $\lambda$ and concentration $c$ (the latter only for the satellites with NFW halos) are indicated. We recall that the isothermal models have a fixed core radius $r_c = 0.035 r_s$, while the disk scale length varies according to $\lambda$. The related model names (used throughout the text) are in the left bottom corner of each panel.

In more realistic NFW halos the scale length of the disks depends not only on $\lambda$ but also on the concentration $c$ and on the halo/disk mass ratio; the more baryons accumulate in the center, the more the whole system contracts in response and thus the smaller is the final scale-length of the baryons. All these aspects are taken into account in the algorithm used for building the galaxies (see Springel & White 1999) but, for the sake of simplicity, we keep the halo/disk mass ratio close to $\sim 50$ in all our models. The reference NFW model with $c = 7$ and $\lambda = 0.065$ (model LIs3 in Figure 1) has the same disk mass and radius of the isothermal model LIs1 but the rotation curve rises more steeply; the rotation curve of the isothermal model is well reproduced by a model with $c = 4$ (model LIs1 in Figure 1). We investigate also the effect of varying only $\lambda$ at fixed $c$; models LIs7s2 and LIs7s4 have $c = 7$ but $\lambda = 0.075$ and $\lambda = 0.1$, respectively (a value of $\lambda$ as high as 0.1 is found in $\sim 30\%$ of halos in cosmological simulations).

We consider different orbital eccentricities, ranging from apo/peric=2 to apo/peric=15 and different disk orientations, although we neglect cases in which the satellites are on retrograde orbits, as it is well known that this configuration strongly inhibits the formation of tidal tails, irrespective of the internal structure of galaxies (Toomre & Toomre 1972; Dubinski et al. 1996; Springel & White 1999; Mayer et al. 2001a,b). The orbits have apocenters between 150 and 250 kpc and pericenters between 20 and 80 kpc, thus encompassing the whole range of galactocentric distances of dSphs.
3 RESULTS

Here we present the results of the simulations in three separate subsections; in 3.1 we will show that we are able to reproduce the observed outer flat profile of Carina and that this happens when the halo of the dwarf has a sufficiently shallow mass distribution or when the orbit is nearly radial; in 3.2 we will analyze the discrepancy between the intrinsic mass loss rates measured in the simulations and those inferred from the observations; finally, in 3.3 we will evolve the tidal debris of spherical dwarf models within a CDM halo extracted from a cosmological simulation and will show how the streams undergo precession and heating by substructure, losing their coherence and becoming difficult to detect.

3.1 Tidal features and the internal structure of satellites

The satellites are severely stripped by the Milky Way tides but a bound stellar and dark component survives until the end of the simulations (\(\sim 10\) Gyr); after a few orbits (the orbital times are of the order of 2-3 Gyr), the stellar disk is transformed into a moderately triaxial system supported by velocity dispersion that closely resembles a dSph (see also Mayer et al. 2001a,b). Figure 2 shows the projected star counts from four representative simulations. In all cases we find tidal streams of stars escaping from the satellites which show up as a flattening of the outer projected star counts. The surface brightness of the tails depends strongly on the orbit and the structure of the initial models; the “strength” of the streams can be quantified simply by the surface density of stars compared to the centrally measured value, \(\Sigma_0/\Sigma_S\). Satellites with cored isothermal halos or low concentration (\(c = 4\)) NFW halos can reproduce very closely the extended flattened star counts observed in Carina (Majewski et al. 2000), for which \(\Sigma_0/\Sigma_S \approx 10^{-2}\). Moreover, the observations are reproduced even for orbits with moderate eccentricities (apo/peri=2-3) for these initial galaxy models.

Instead, the streams are too weak to match the observations if the concentration is as high as \(c \approx 7\), unless the orbits are nearly radial (Figure 2). In fact, raising the concentration by a factor of 2 leads to an increase of nearly 30 \% in the escape speed at the half mass radius of the stars where the rotation curve peaks. (This also increases their robustness to tides since its response will be more adiabatic, see section 3.2.) In this case \(\Sigma_S/\Sigma_0 \lesssim 10^{-3}\). This is true even when the satellite is constructed with \(\lambda\) considerably larger than the mean and thus acquires a larger disk scale-length (as in the case of the model LNC7s4 shown in Figure 2). In fact, the value of the concentration is the most important parameter in determining the amount of stripped material; a change in the spin affects only the disk-scale length, while a change in the concentration affects both the scale-length and the central density of the halo, or, equivalently, its local escape speed. However, if the initial disk scale-length is substantially decreased while keeping the disk mass fixed, the resulting higher surface density of the disk can affect its evolution enhancing the non-axisymmetric instabilities that drive the morphological transformation; in fact, in model LIs3, the high self-gravity of the compact disk leads to a strong bar instability and later to a very compact stellar remnant, thereby inhibiting the developing of tidal tails (see also Mayer et al. 2001b).

The simulations show that the visible strength of tidal extensions is sensitive to projection effects. The results by Majewski et al. (2000) show a strong flattening of the star counts at a distance comparable to the tidal radius of the dwarf galaxy, where the counts level out at \(\sim 10^{-2}\) the peak value. The feature is more prominent when the line of sight of the observer falls along one of the tidal tails, because the projected surface density of the tails is maximally enhanced in this case. When viewed perpendicular to the orbit, the tails can be more easily separated from the bound stars visually, but in this case they have the lowest surface density (indeed corresponding to the actual intrinsic value), \(\mu_B > 30\) mag arcsec\(^2\).

In Figure 3 we show in more detail the results for the satellite models LIs1 and LNCs1 with \(V_c = 25\) km/s (these have an initial total mass of only \(5.8 \times 10^8 M_\odot\)) as these yield remnants with physical scales close to those of Carina. Infact, we note that the flattening of the star counts occurs at 1-2 kpc from the center, the core radius of the bound remnant estimated from the fit with a King model with \(c = 0.5\) is around 500 pc and the luminosity of the remnants is \(M_B \sim -11\), assuming a final stellar mass-to-light ratio of 5 (as derived by combining population synthesis models

\[ \Sigma_0/\Sigma_S \approx 10^{-2} \]

\[ \Sigma_S/\Sigma_0 \lesssim 10^{-3} \]

\[ \mu_B > 30\text{ mag arcsec}^2 \]

\[ \Sigma_0/\Sigma_S \sim 10^{-2} \]

\[ \Sigma_S/\Sigma_0 \lesssim 10^{-3} \]
with a model for the star formation history as described in Mayer et al. (2001)). The final dark matter mass is almost 5
with a model for the star formation history as described in
Figure 3.

Projected star counts obtained for the remnant of
by no more than a factor
Asymmetrical contamination introduced by tidal tails. How-
or an apparent rotation would also be observed due to the
caused by unbound stars in projection; as already noted by
to an overestimate in the velocity dispersions of the dwarf
obtained by Lake (1990) for galactic dwarf spheroidals.
(Mateo 1998) and comfortably higher than the lower limit
would be around 25 for a stellar mass-to-light
in the central region of dwarfs are at most
∼ 40% larger
by nearly an order of magnitude.

In general, the presence of tidal extensions will lead to
an overestimate in the velocity dispersions of the dwarf
caused by unbound stars in projection; as already noted by
others before (e.g. Piatek & Pryor 1992), a velocity gradient
or an apparent rotation would also be observed due to the
asymmetrical contamination introduced by tidal tails. How-
ever, in our simulations the apparent velocity dispersions
in the central region of dwarfs are at most ∼ 40% larger
than the intrinsic value, which would inflate the measured
$M/L$ by no more than a factor ∼ 2 (giving $M/L \lesssim 50$
in the remnants LNe4s1 and LIs1). Figure 4 clearly shows that
only measurements extending a few kpc’s from the center
would be significantly altered; therefore the contamination of
kinematics induced by tails would not explain the high
fractional mass loss rates measured in the simulations
( obtained by simply dividing the total mass lost by the du-
ration of the simulation of about 10 Gyr) are significantly
lower, ∼ 0.06 Gyr$^{-1}$.

One problem in the application of the formula is the
assumed radial surface density profile of the stream. In fact,
the outer star counts profile of our remnants are much flatter
than $r^{-1}$ for most of the viewing projections. Removing
the constraint on the profile of the extra-tidal stars, Johnston
et al. (1999) derive also an upper limit for the mass loss rate:

$$\frac{df}{dt} = \cos(\theta) \frac{\Sigma_{\text{ext}}(\tau_{\text{break}})}{n_{\text{break}}} \frac{\pi}{T_{\text{orb}}} 2\pi \tau_{\text{break}}^2$$

where $\theta$ is the angle between the velocity vector of the
satellite and the line-of-sight (which can be derived for those
satellites that have measured proper motions), $n_{\text{break}}$ is the
number of stars counted within $r_{\text{break}}$ (the radius where the
profile changes slope) and $T_{\text{orb}}$ is the orbital time. Using
Equation (1) for the cases with clear tidal features we obtain
$df/dt < 0.5$ Gyr$^{-1}$, which is still not representative of the
numerical results, being higher than the real mass loss rate
by nearly an order of magnitude.

Equation (1) is derived under the assumption that the
stars are lost continuously over the orbital time $T_{\text{orb}}$. How-
ever, the tidal mass loss for a satellite moving on an eccen-
tric orbit will occur mostly as a result of the tidal shocks suffered
at pericenter and will depend on its ability to respond to
the perturbation and adjust to a new equilibrium. To gain a
better insight into the mechanism, we can consider a galaxy
that suffers a tidal shock of duration $\tau = R_p/V_p$, where
$R_p$ and $V_p$ are, respectively, the distance and the velocity
of the galaxy at the pericenter of the orbit. The charac-
teristic time required for a star at the disk half mass radius
$r_{1/2}$ to increase its mean-square velocity $< v^2 >$ due to the
shock is $t_{\text{shock}} \sim \tau V_c^2 / < \Delta v^2 >$, where $V_c$ is the internal
(rotational) velocity of the galaxy and $\Delta v$ is the velocity

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure3.png}
\caption{Projected star counts obtained for the remnant of model LIs1 (filled circles) and model LNe4s1 (open circles with $V_c = 25$ km/s, both observed along one of the tidal tails. The dots with error bars are the number counts from Majewski et al. (2000) averaged over the four samples of giant stars. Fits with King profiles with $c$=0.5, 1, 1.5 (where $c = \log_{10}(r_{\text{break}} / r_0)$) are also shown (solid, short dashed and long dashed lines, respectively).}
\end{figure}
impulse; this timescale will be comparable to the characteristic timescale of mass loss (see Binney & Tremaine, 1987). Gnedin, Hernquist & Ostriker (1999) have provided analytical formulas to calculate $\Delta v$ for a satellite that is shocked by an extended perturber with an isothermal profile including even the adiabatic corrections that account for the motion of the stars within the galaxy. As shown by the authors, if the orbits are eccentric, a good approximation is obtained by simply assuming that the satellite is moving on a straight path. In the latter case we can write

$$<\Delta v^2> = \left(\frac{GM_0}{R_\text{p}V_p^3}\right)^2 \frac{r^2\pi^2}{3} \frac{R_\text{p}^3}{R_\text{max}} \times (1 + \omega\tau)^{-2.5}$$  \hspace{1cm} (2)$$

where $M_0$ and $R_{\text{max}}$ are the total mass and radius of the perturber and the last term in the product is the first-order adiabatic correction ($\omega$ is the typical stellar frequency at $r = r_{hm}$, and $\omega\tau = \tau/\text{t}_{\text{dyn}} \sim 1$ in our models, where $t_{\text{dyn}}$ is the dynamical time at $r = r_{hm}$). For a satellite with $V_c = 25$ km/s and $r_{hm} = 2$ kpc on the apo/peri=3 orbits in our simulations ($R_\text{p} = 75$ kpc, $V_p \sim 300$ km/s), we obtain $t_{\text{shock}} \sim 5$ Gyr. We can consider $t_{\text{shock}}$ as an estimate of the characteristic time over which the satellite loses 50% of its initial disk mass.

As we can see from Figure 5, the satellites on apo/peri=3 orbits actually have lost about 40% of their mass 5 Gyr after the first tidal shock. Although in the simulations more than one shock occurs, the non-axisymmetric instabilities have a counteracting effect, as they make the stellar component more concentrated and increase the adiabatic corrections over time (see Mayer et al. 2001b), thereby explaining the good agreement with the above simple estimate.

The resulting average fractional mass loss rate is $\sim 0.1$/Gyr. The agreement with the simulations strongly depends on the adiabatic corrections; if we neglect them then the resulting mass loss rate would be higher by a factor of 5 and would be close to the predictions of Johnston et al. (1999). In the inner regions of the system the adiabatic corrections will be increasingly more important and will increase substantially the overall lifetime of the satellite.

Using the numerical results as a guide we propose a simple recipe to infer the mass loss rate from the observed star counts profile; on typical orbits as those considered here the dwarfs lose mass at a rate that scales as $\sqrt{(\Sigma_S/\Sigma_0)}$.
employing the simulations that match the data on Carina
to calibrate our estimate (these yield a fractional mass loss
rate $df/dt \sim 0.06 \, \text{Gyr}^{-1}$), we obtain $df/dt \sim 6\sqrt{(S_\Sigma/\Sigma_0)}$
Gyr$^{-1}$. This result was derived for the satellites on orbits
with apo/peri= 3, but the mass loss rates on nearly radial
orbits differ by less than a factor of 2 (see Figure 5).

3.3 Precession and heating of tidal streams

For dwarfs orbiting in spherical and smooth potentials like
those considered so far the escaping stars form symmetric
tidal tails that lead and trail the satellite revealing its fu-
ture and past orbit (see also Moore & Davis 1994). However,
in general the orbital evolution of the streams will depend
on the structure of the underlying potential and in turn the
streams might be used as a tracer of such structure only pro-
vided that they remain sufficiently coherent (Johnston et al.
1999a, Zhao et al. 1999). Cold dark matter halos are complex
triaxial systems with shapes and angular momenta that vary
considerably from the center to their virial radii (Moore et al
2001). They also contain dark matter substructure and satel-
lite galaxies that can heat and perturb parts of the stream
away from their orbital paths. These effects might combine
to destroy the coherent nature of tidal streams through dif-
f erential precession of orbits (see also Johnston, Sackett &
Bullock 2001).

To investigate the long-term evolution of tidal tails we
construct a massless spherical system using 50,000 particles
distributed with a density profile $\rho(r) \propto r^{-1}$, radius 10 kpc
and velocity dispersion $\sigma_{td} = 10 \, \text{km/s}$. This unbound test
satellite will form tidal streams that can be used to explore
orbits within different halos. The evolution of this system on
a series of circular orbits within a smooth spherical potential
is shown in Figure 6. This potential is a singular dark matter
halo with density profile $\rho(r) \propto r^{-2}$ with constant velocity
dispersion $\sigma_{\text{halo}} = 200/\sqrt{2} \, \text{km/s}$. The rings of debris cor-
respond to satellites on initially circular orbits at radii of
0.2, 0.4, 0.6, 0.8, 1.0 \text{r}_{200} \text{ where } \text{r}_{200} = 300 \, \text{kpc}.
The satellite is unbound and immediately starts to form
symmetric tidal tails because the model has a finite size and
the particles have random velocities. The tidal debris lies in
the orbital plane and after a time scale of 6 Gyr the particles
lie in streams that wrap around more than one orbit at the
center of the potential and about 10% of an orbital radius
at the edge.

We now repeat the test using a CDM halo taken from
one of the cosmological simulations of Moore et al. (1999a).
By construction, the circular velocity and virial radius are
similar to those adopted in the spherical potential above.
The halo is resolved with $10^6$ particles within $R_{200}$ and we
use a comoving softening length of 0.5 kpc. This particular
galactic mass halo virialises by a redshift $z=0.5$ and does
not accrete any bound object containing more than 15%
of its mass by the present day. We calculate the axis with the
largest component of angular momentum and place the test
satellites in circular orbits at the same radii as used in the
spherical potential above.

Figure 7 shows the satellite particles after a period $\sim 6$
Gyrs revealing that the tidal streams have precessed dra-
matically away from their initial orbits. The inner streams
have wrapped several times around the halo, both within

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure6.png}
\caption{The evolution of 5 massless satellites on circular orbits within a smooth spherical potential for a period of 6 Gyr (comparable to the orbital time of the outer streams). The left panel is an edge on view of the orbital plane and the right panel is a face on view.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure7.png}
\caption{The evolution of 5 massless satellites on initially circular orbits (same as in Figure 6) within a CDM galactic mass halo. The satellites are introduced at a redshift $z=0.5$ and the simulation is continued to the present day. The left panel is an edge on view of the initial orbital plane and the right panel is a face on view.}
\end{figure}

and out of the orbital plane whilst the outer streams remain
more coherent but have precessed from their initial orbital
plane by over 45 degrees. The precession from the differen-
tially rotating triaxial halo structure is mostly responsible
for the differences between the orbits of the tidal debris be-
tween Figure 6 and Figure 7. However, the substructure in
the galactic CDM halo has also contributed visible heating
to the streams. This is most noticeable in the outer streams
which have a clumpy appearance due to heating by the most
massive subhalos. (Dark matter substructure in the outer
halo will be more massive and cause the most heating.). Nu-
merical heating of the streams due to massive halo particles
(Moore et al. 1996) might somewhat enhance the observed
evolution of the streams. In order to test our results we ran
a massless spherical satellite in a $10^5$ particles Milky Way-
sized halo with an NFW profile; this halo is similar to the
CDM halo as far as profile, mass and radius are concerned
but it is spherical and does not have substructure, there-
fore no physical heating or precession is expected. After 10
Gyr we measured fluctuations of only a few percent in the
orbital energy and orbital angular momentum, and, corre-
spondingly, the initial orbital plane of the satellite is barely
altered; this shows that two-body heating has a negligible
contribution to the evolution of the streams (this is a conser-
The dissipative effects of a baryonic component that would help regularise the structure of the inner dark matter halo. However, the outer halo would remain unaffected by the adiabatic contraction and this tends to produce oblate inner halos (Dubinski & Carlberg 1991). Coherent streams should only be found in the plane of the disk or on polar orbits. Our results suggest that using streams to constrain the potential structure of galactic halos will be complicated by these effects. Evidence of streams on great circles in galaxy and cluster halos would support models in which the dark matter behaves like a fluid. In this case, halos are highly spherical and contain less mass attached to subhalos due to ram-pressure stripping. Interestingly, the stream associated with the Sagittarius dwarf spheroidal appears as a great circle; Ibata et al. (2001), based on the analysis of the latter, have recently argued that the Galactic halo must be nearly spherical between 16 and 60 kpc from the center.

4 DISCUSSION

We have shown that the outer flattening observed in the stellar profiles of some dSphs can provide a useful constraint on the structure of their dark matter halos once their orbital eccentricity is known. At present, the few proper motions available (e.g. Kroupa & Bastian 1997 for the LMC and eccentricity is known. At present, the few proper motions on the structure of their dark matter halos once their orbital stellar profiles of some dSphs can provide a useful constraint spherical between 16 and 60 kpc from the center.

4.1 High mass to light ratios in dSphs

Our results have implications on the actual dark matter content of dSphs. Large tidal tails are produced only when the dark matter in the remnants accounts for $\leq 80\%$ of the total mass. The apparent $M/L$ can be at most two times higher than the intrinsic value because of the unbound stars projected along the line of sight and therefore we expect to find tidal tails only around dwarfs whose measured $M/L$ is not very high. Indeed most of the dSphs in the Local Group, including Carina, have $M/L \leq 30$ (Mateo 1998).

The dark matter contents of Draco and Ursa Minor, having $M/L > 60$ (Hargreaves et al. 1994a,b, Mateo 1998) are instead too high even accounting for enhanced apparent velocity dispersions. Such high dark matter contents would be incompatible with the observations of massive tails; the remnants that have similarly large dark matter contents at the end of our simulations (see also Mayer et al. 2001a,b on the evolution of the GR8 model) have star counts at the level $\Sigma_S/\Sigma_0 < 10^{-3}$ in the outer part.

Although very recent results exclude the presence of tails in Draco (Odenkirchen et al. 2001; Aparicio et al. 2001), other authors have reported positive detections of some extra tidal stars around the latter dwarf and Ursa Minor (Piato et al. 2001, Martínez-Delgado et al. 2001). In order to further explore this issue we ran a simulation with a satellite model different from those used so far. We used an NFW halo with a high concentration, $c = 11$, and $V_c = 25 \text{ km/s}$, and a disk extending out to half of the virial radius of the halo, $\approx 10 \text{ kpc}$, corresponding to a high spin parameter, $\lambda = 0.16$, and a very low central surface brightness, $\mu_B \sim 25 \text{ mag arcsec}^{-2}$.

We placed the model on an orbit with an apo/peri= 2 and a pericenter $R_p = 55 \text{ kpc}$, consistent with the present distances and radial velocities of Draco and Ursa Minor (Mateo 1998). After 7 Gyr the satellite has turned into a dSph ($v_{rot}/\sigma \sim 0.3$) with a central velocity dispersion $\sigma \sim 10 \text{ km/s}$ and a dark matter halo still 7 times more massive than the stellar component; this would yield $M/L > 40$ for a stellar mass-to-light ratio $\sim 5$ (Mayer et al. 2001b). Furthermore, due to its unusually large scale length, the stellar component has undergone severe stripping, producing prominent tidal tails and signatures in the star count profile qualitatively similar to those observed in Carina (Figure 8): including possible projection effects due to the tidal tails, the apparent mass-to-light ratio could be enhanced up to values around 80. This experiment shows that an extremely extended disk can produce large tails notwithstanding the high central dark matter density of the halo. However, a closer look shows that the remnant is very extended in radius and the flattening of the star counts in the remnants occurs at more than 4 kpc, which is too far out compared to the size of Draco, the latter being less than 1 kpc (Mateo 1998). In addition, a dwarf progenitor with an extremely extended disk is hard to support from the observational point of view; the rotation curves of dIrrs and LSB spirals suggest that the scale-lengths of halos and baryons are correlated (de Blok & McGaugh 1997) and in some cases the scale-length of the halo can be larger than the typical disk size (Lake & Skillmann 1990), while in the present model is considerably smaller. In the present model would clearly cause Besides, the surface density of the gas in the outer part of such an extended disk would be so low that the star formation would have hardly occurred, making the formation of stellar tails unlikely.

The correct evaluation of the $M/L$ of dSphs is important when one tries to compare the observed number of Galactic satellites with the numbers predicted by cosmological N-body simulations (Moore et al. 1999; Klypin et al. 1999). It has been pointed out that dwarfs with NFW halos should have rising velocity dispersion profiles and that
by using the measured central velocity dispersions one would actually underestimate the total mass of dSphs (White 200); including this correction would improve the agreement with observations (Moore 2001).

Our simulations suggest two possible scenarios with regard to this issue and both are highlighted in Figure 4. First, if it were confirmed that most of the satellites have large tidal tails and that their orbits have low eccentricity, then it is very likely that their halos have low concentrations, $c < 7$, and have quite flat intrinsic and apparent velocity dispersion profiles; the apparent velocity dispersion can actually be higher than any value of the intrinsic velocity dispersion, but never smaller, which would actually tend to reverse the correction, (cfr. Figure 4a). Secondly, even if the satellites had more concentrated NFW halos (1) the intrinsic peak velocity dispersion is only $\sim 25\%$ higher than the central value in the remnants and (2) the intervening tidal debris, though quite weak, tend to flatten even further the apparent velocity dispersion profile (cfr. Figure 4b). Hence, it seems that a better assessment of the actual mass of the dwarfs derived from apparent velocity dispersions would never solve the substructure problem and could actually make it worse.

**Figure 8.** Projected star counts for the remnant (after 7 Gyr) of a satellite model with a highly concentrated halo. The satellite has $V_c = 25$ km s$^{-1}$ and was placed on an orbit with apo/peri $= 2$ and $R_p = 55$ kpc. We show the projected star counts along one of the tails (solid line) and along the two lines of sight perpendicular to the former (short dashed and long dashed lines).

5 SUMMARY

We have used numerical simulations of two component models of dwarf galaxies orbiting within a Milky Way potential to study the effects related to their tidal tails. The signatures produced by the tidal debris in the stellar profiles can be used to constrain the structure of the dark matter halos of dwarfs, providing hints to the nature of the dark matter. The long term evolution of tidal debris was followed within a smooth spherical potential and within a high resolution cold dark matter halo. We summarize our conclusions here:

- We can produce tails as prominent as observed around the Carina dSph for models with soft central potentials or singular potentials on highly radial orbits. Knowledge of the orbits of the dSphs is vital to constrain directly their internal structure. If it will be confirmed that the orbits are nearly circular, warm dark matter models will be favored instead of cold dark matter.
- Models with very high mass to light ratios and strong tidal tails are very difficult to produce. Draco and Ursa Minor should only have very weak tails, at a star count level at least ten times lower than that found in Carina.
- Our simulations provide a simple estimate of the mass loss rates of dSphs based on star counts and these are significantly lower than those obtained by others discarding adiabatic corrections; Carina is likely to survive for at least another 5 Gyr.
- Only satellites on very tightly bound orbits like Sagittarius, that suffered many strong tidal shocks, could have been already destroyed in the past or could be now close to disruption.
- Central velocity dispersions of stars in dSphs are good indicators of the characteristic peak velocity dispersions of their dark matter halos, i.e. tidal heating produces nearly isotropic orbits and quite flat velocity dispersion profiles.
- The masses of dwarf spheroidals could be overestimated when large tidal tails are present but the maximum effect due to projection of unbound stars is only a factor of two. However, this would shift the mass function of galactic satellites further away from that predicted by cold dark matter models, making the substructure problem even worse.
- The tidal debris within a cold dark matter halo shows dramatic signatures of differential precession and some heating by dark matter substructures. It may be impossible to use observations of tidal streams to map the structure of the Galactic halo.
- If many examples of coherent tidal streams are discovered, then this would favor fluid dark matter models which produce smoother and highly spherical dark matter halos.

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