Near-Field Cosmology with Dwarf Elliptical Galaxies
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The mass of dwarf spheroidal galaxies and the missing satellite problem

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Abstract. We present the results from a suite of N-body simulations of the tidal stripping of two-component dwarf galaxies comprising some stars and dark matter. We show that recent kinematic data from the local group dwarf spheroidal (dSph) galaxies suggests that dSph galaxies must be sufficiently massive (10^9–10^{10}M$_\odot$) that tidal stripping is of little importance for the stars. We discuss the implications of these massive dSph galaxies for cosmology and galaxy formation.

Keywords. dwarf, dark matter, Local Group, kinematics and dynamics, interactions

1. Introduction

In the current cosmological paradigm all structure forms from the successive mergers of smaller substructures (see e.g. White & Rees 1978). Cosmological N-body simulations demonstrate that much of this substructure will survive up to the present epoch in the form of dwarf galaxies (Navarro *et al.* 1996). While it is well known that cold dark matter (CDM) theories over-produce this substructure, this 'sub-structure problem' can be solved by either suggesting that only the most massive substructure halos form stars (Stoehr *et al.* 2002); or by suppressing small scale power (Avila-Reese *et al.* 2001 and Zentner & Bullock 2002).

Either way, these solutions suggest that dSph galaxies in the local group must be massive – some $\sim 10^9$–10^{10}M$_\odot$ in total mass. At this mass, for all but the most extreme plunging orbits, tidal stripping would not affect the central stars and gas (Hayashi *et al.* 2003).

In contrast to this picture, there is compelling evidence to suggest that tidal stripping could be extremely important for the formation and evolution of the local group dSph galaxies. Walcher *et al.* (2003) and Wilkinson *et al.* (2004) point out that all of the local group dSph galaxies observed with deep enough photometry have a break in the light profile which is similar to that observed in tidal stripping simulations (see e.g. Aguilar & White 1986, Johnston *et al.* 2002 and Gómez-Flechoso & Martínez-Delgado 2003). Furthermore, Mayer *et al.* (2001b) and Mayer *et al.* (2001a) have suggested that the very low internal angular momenta and spheroidal morphologies observed in local group dSph galaxies could be explained by tidal effects. However, to experience strong tidal effects, the local group dSph galaxies must reside in low mass dark matter halos ($\lesssim 10^9$M$_\odot$) which appears to be at odds with naive cosmological predictions.

Kazantzidis *et al.* (2004) and Kravtsov *et al.* (2004) have recently argued that dSph galaxies might not inhabit the most massive substructure halos. Kravtsov *et al.* (2004) suggest that reionisation sets an *epoch* at which the smallest collapsed structures cannot form stars, rather than having a mass scale below which star formation ceases. This can

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go some way towards solving the mystery, but not all of the way: even in the scheme proposed by Kravtsov *et al.* (2004) dSphs must inhabit the more massive halos on average.

In order to resolve these issues we really require more observational constraints from the local group dSph galaxies. Recently Wilkinson *et al.* (2004) have found a sharp fall-off at ∼1 kpc in the projected velocity dispersion of both the Draco and Ursa Minor (UMi) dSph galaxies. At first glance, these data would seem to rule out the tidal stripping model. It is well known that tidal stripping produces heating of stars within the tidal radius (see e.g. Oh *et al.* 1995 and Gómez-Flechoso & Martínez-Delgado 2003). Thus the existence of a cold population at ∼1 kpc suggests that the tidal radius must lie beyond this point and that dSph are then 'high mass' galaxies.

In this paper we examine this argument more carefully. We present the results from a suite of N-body numerical simulations of the tidal stripping of two component dwarf galaxies comprising some stars and dark matter, in orbit around a Milky Way-like galaxy.

2. Results

The initial conditions for the dwarf galaxies were set up as in Kazantzidis *et al.* (2004), but for two-component spherical galaxies comprising a dark matter halo and some stars. The satellite galaxies were well resolved with 10^5 star and 10^6 dark matter particles.

The N-body integration for the orbit of the dwarf galaxy about the Milky Way was then performed using a modified version of the GADGET N-body code Springel *et al.* (2001). The code allowed for a fixed potential to be introduced to model the Milky Way. We used a Miyamoto-Nagai potential for the Milky Way disc and bulge and a logarithmic potential for the Milky Way dark matter halo. The simulations, initial conditions and model parameters are described in more detail in Read *et al.* (2005).

Figure 1 shows the results for three very different dwarf galaxies on orbits around the Milky Way after ∼10 Gyrs. In each case the orbiting galaxy is currently at apocentre.

The first model (model A) is one in which the satellite galaxy contains *no dark matter*. It was a Plummer sphere Binney & Tremaine (1987) with total mass and scale length of $10^7 M_\odot$ and 0.23 kpc. The galaxy was placed on a plunging orbit with apocentre and pericentre of 80 and 20 kpc respectively. Notice, as published by previous authors, that the isodensity contours (left panel) show the tidal 'S-shape' caused by the leading and trailing tidal debris. Several authors have argued that there is evidence for such shapes in the isodensity contours of the local group dSph galaxies (see e.g. Gómez-Flechoso & Martínez-Delgado 2003 and Munoz *et al.* 2005); and that this, therefore, implies that the local group dSph galaxies must be strongly tidally distorted. Consider, however, the middle panel for the line of sight velocities. There is a strong velocity gradient across the the galaxy which is not observed in Draco or Ursa Minor (UMi) (Wilkinson *et al.* 2004). Furthermore, the projected velocity dispersion is rising beyond the tidal radius, whereas in both Draco and Ursa Minor it is observed to drop sharply (Wilkinson *et al.* 2004). Projections which give distorted isodensity contours, small velocity gradients and near-flat projected velocity dispersions are very rare Read *et al.* (2005). In *no* projection was the projected velocity dispersion of the stars found to fall.

Even if we are viewing the local group dSph galaxies from a projection which minimises any kinematic trace of tidal stripping, notice that the central velocity dispersion in model A is much smaller than that observed in the Draco dSph galaxy (see data points with large crosses). As shown by Kleyna *et al.* (2001), the only way to reproduce such a large central velocity dispersion with the stars we see in Draco is to introduce a significant dark matter component (and see also Klessen *et al.* 2003).

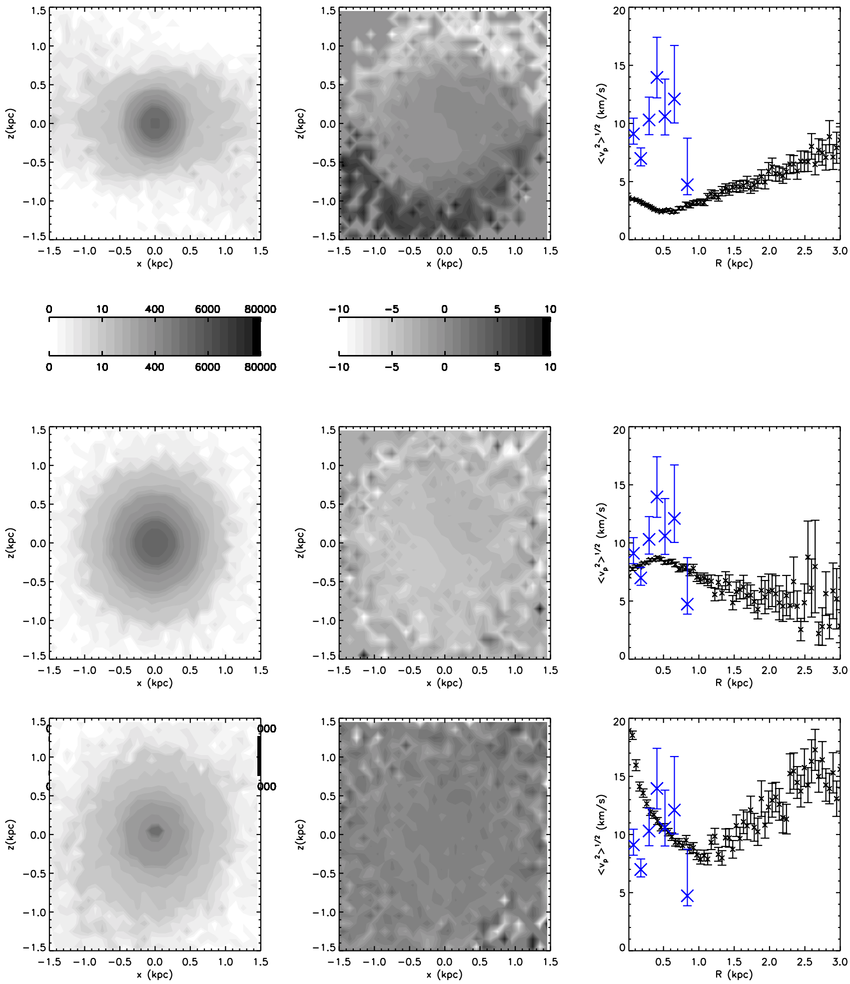

Figure 1. Results from three models: A (top); B (middle) and C (bottom). Left panels show the projected surface density of the stars, the middle panels show the line of sight velocities of the stars and the right panels show the projected velocity dispersion of the stars as a function of radius. The contour bars beneath the top left and middle panels show the number of star particles and the projected velocity in km/s respectively. Over-plotted on the right panels (large crosses) are the data points from the Draco dSph galaxy (Wilkinson *et al.* 2004).

Model B contained a significant Plummer dark matter component with mass $14 \times 10^7 \mathrm{M}_\odot$ and scale length 0.5 kpc; its orbit was identical to model A. Even after 10 Gyrs the galaxy has regular isodensity contours, no velocity gradient and a falling projected velocity dispersion. This is because the initial mass and concentration of dark matter was chosen to be sufficiently high that tidal stripping produced almost no effect on the stars over 10 Gyrs. Notice that for this model, the central velocity dispersion is much closer to that of Draco.

Finally, model C was chosen to have a dark matter halo consistent with those observed in cosmological simulations. We used a Hernquist profile with mass $10^{10}\mathrm{M}_\odot$ and scale length 1.956 kpc. In order for it to have a final velocity dispersion low enough given this starting mass we had to choose an extreme orbit with a pericentre of just 6 kpc†. At

† The central velocity dispersion is much lower than in the initial conditions for this model

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this radius the galaxy would likely affect the Milky Way disc (and dynamical friction would become important) and so already the orbit is quite unrealistic. However, notice that even for such an extreme orbit, the central velocity dispersion is still too large after 10 Gyrs to be consistent with Draco.

In conclusion, tidal stripping cannot be very strong for many, if not all, of the local group dSphs. Strong tidal stripping, which would produce distorted isodensity contours, also leads to velocity gradients and flat or rising projected velocity dispersions - neither of which are observed in the local group dSphs for which we have good kinematic data (but see also Munoz *et al.* 2005). This suggests that dSph galaxies must be sufficiently massive such that tidal stripping is of little importance for the stars. Either they are on orbits with large pericentres, in which case they can have masses as low as $\sim 10^8 M_\odot$ Kleyna *et al.* (2001); or they are on more extreme orbits in which case they must be $\sim 10^9$–$10^{10} M_\odot$ depending on the extremity of the orbit. Our current cosmological paradigm would favour the latter hypothesis, but this leaves us with a puzzle: if the dSph are really as massive as $\sim 10^{10} M_\odot$ and have dark matter densities which are cosmologically consistent then they would have central velocity dispersions which are too large to be consistent with Draco or UMi - even after significant tidal stripping and shocking.

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due to disc shocking and tidal stripping (see Read *et al.* (2005) for more details). It does tend to zero at the centre as it should, but this is disguised somewhat by the choice of bin size.

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Discussion

Diemand: In the NFW model the projected stellar velocity dispersion droped to about 0.5 of the initial value. Does $v_{c,max}$ of the dark matter profile go down by a similar factor?

Read: Good question. Certainly the change in the central density is comparable to results from Kazantzidis *et al.* I couldn't say how much v_c drops, but I will certainly look at that.