Tidal Stirring of Milky Way Satellites: A Simple Picture with the Integrated Tidal Force

Ewa L. Łokas, Stelios Kazantzidis, Lucio Mayer and Simone Callegari

Abstract Most of dwarf spheroidal galaxies in the Local Group were probably formed via environmental processes like the tidal interaction with the Milky Way. We study this process via N-body simulations of dwarf galaxies evolving on seven different orbits around the Galaxy. The dwarf galaxy is initially composed of a rotating stellar disk and a dark matter halo. Due to the action of tidal forces it loses mass and the disk gradually transforms into a spheroid while stellar motions become increasingly random. We measure the characteristic scale-length of the dwarf, its maximum circular velocity, mass, shape and kinematics as a function of the integrated tidal force along the orbit. The final properties of the evolved dwarfs are remarkably similar if the total tidal force they experienced was the same, independently of the actual size and eccentricity of the orbit.

1 Introduction

In the tidal stirring scenario for the formation of dwarf spheroidal (dSph) galaxies [8] the progenitors are late type dwarfs affected by tidal forces from the Milky Way or any other normal size galaxy. A similar process may lead to the formation of S0s in galaxy clusters [2, 3]. In the absence of any analytical description of tidal effects for dwarfs on eccentric orbits, that seem to dominate in ΛCDM cosmologies, the problem can be fully addressed only via N-body simulations. With this tool, the tidal stirring scenario has been recently tested for a variety of orbits and structural parameters of the dwarfs and shown to work very efficiently towards the formation

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Table 1 Orbital parameters of the simulated dwarfs

Orbit	r_{apo} [kpc]	r_{peri} [kpc]	T_{orb} [Gyr]	t_{la} [Gyr]	n_{apo}
O1	125	25	2.09	8.35	5
O2	87	17	1.28	8.95	8
O3	250	50	5.40	5.40	2
O4	125	12.5	1.81	9.05	6
O5	125	50	2.50	10.00	5
O6	80	50	1.70	8.50	6
O7	250	12.5	4.55	9.10	3

of dSph galaxies [9, 5, 6, 4, 7]. It was demonstrated that during the tidal evolution the dwarfs lose mass via tidal stripping, they undergo morphological transformation from disks to spheroids and the rotation of their stars is replaced by random motions.

The exact mechanism behind this transformation still eludes us however. It is generally believed that the processes shaping the dwarf galaxies orbiting on eccentric orbits may be inherently different from those on circular orbits due to the time-dependence of the tidal force. While on circular orbits tidal forces are believed to mainly steepen the outer density profile, on eccentric orbits they likely induce strong shocks to the whole structure of the dwarf galaxy at pericenters [1]. It has also been suggested however [8] that the key factor that controls the extent of transformation is the integrated tidal force the dwarf experiences along the orbit rather than the particular shape of the orbit. Here we address this question using a subset of collisionless *N*-body simulations described in detail in [4].

In these numerical experiments a dwarf galaxy, initially composed of a stellar disk and a dark matter halo, is placed on seven different orbits O1-O7 around a live Milky Way model. The orbital parameters of the simulations are listed in Table 1. Orbits O1-O5 correspond to runs R1-R5 in [4], while orbits O6 and O7 are two additional setups. The second and third column of the Table list the apo- and pericenter distances and the fourth one the orbital time. All simulations were evolved for 10 Gyr; the fifth column gives the time when the last apocenter occurred and the last column the total number of apocenters.

Our dwarf galaxy model was identical in all runs (model D1 in [4]). It contained a stellar disk of mass $M_{\rm d} = 2 \times 10^7$ $\mathrm{M}_{\odot}$ with scale-length $R_{\rm d} = 0.41$ kpc and thickness parameter $R_{\rm d}/z_{\rm d} = 0.2$. The dwarf's dark matter halo had an NFW profile with virial mass $M_{\rm h} = 10^9$ $\mathrm{M}_{\odot}$ and concentration $c = 20$. The mass distribution of the Milky Way was given by model MWb in [10].

2 Results

For each of the simulations we calculated the evolution of a few key properties of the dwarf in time: the characteristic radius $r_{\rm max}$ at which the circular velocity has a maximum, the maximum circular velocity $V_{\rm max}$, and the mass contained within the

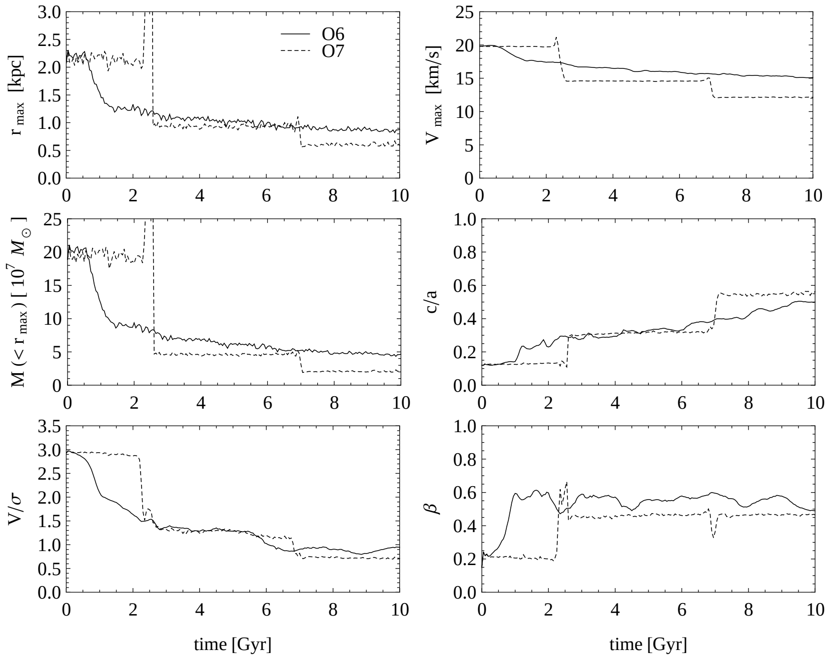

Fig. 1 Evolution of the properties of the dwarf as a function of time for the least (O6, solid line) and the most (O7, dashed line) eccentric orbit.

characteristic scale, $M(< r_{\rm max})$. Using stars inside $r < r_{\rm max}$ we determined the shape and kinematic properties of the stellar component. The shape is described in terms of the shortest to longest axis ratio c/a calculated from the moments of the inertia tensor. The amount of ordered versus random motion was quantified by the ratio of the rotation velocity around the shortest axis to the 1D velocity dispersion, V/σ. The anisotropy of the stellar motions was characterized by the usual β parameter. The evolution of these properties as a function of time is illustrated in Figure 1 for the least and the most eccentric orbit (O6 and O7). The results for other orbits are discussed in [4].

Next, we calculated the tidal force experienced by the dwarf galaxy on different orbits as

$$F_{\rm tidal} \propto r_{\rm max} M(< R)/R^3 \,, \quad (1)$$

where $r_{\rm max}$ is the characteristic scale-length of the dwarf at which the tidal force operates, R is the distance between the center of the dwarf and the center of the Milky Way and $M(< R)$ is the mass of the Milky Way model within this distance (approximated as a spherical NFW distribution with the disk and the bulge added as point masses). Summing up contributions of this form over a given orbit we obtain an estimate of the integrated tidal force (ITF) experienced by the dwarf up to a given time. To make the results comparable for different orbits it is advisable to integrate

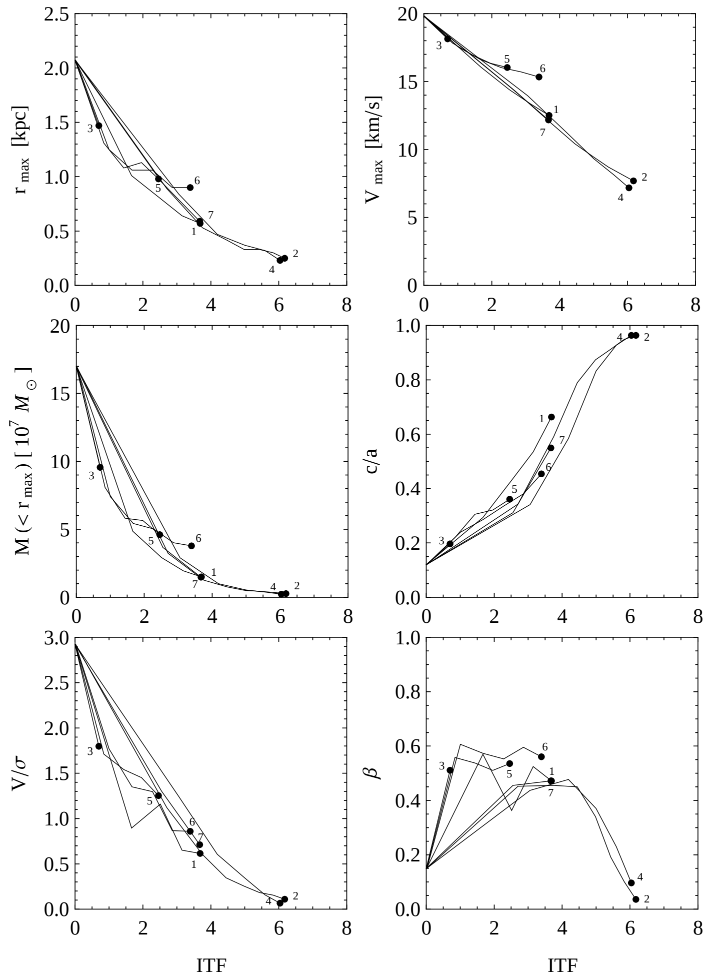

Fig. 2 Evolution of the properties of the dwarf as a function of the integrated tidal force (ITF, in arbitrary units). The lines connect measurements at subsequent apocenters for a given orbit with dots marking the results at the last apocenter. In each panel all lines start from the same point at ITF=0 because the initial structural properties of the dwarf were the same for all orbits and all simulations started at apocenters.

over full orbital times so for each of the orbits we summed up the tidal force from the first up to the last apocenter.

The evolution of different properties of the dwarf, described above, as a function of the integrated tidal force, is shown in Figure 1. The lines join the results for a given orbit at subsequent apocenters with the dots marking the last apocenter. Numbers near the points indicate the orbit, with 1-7 corresponding to orbits O1-O7 in Table 1. The values of the parameters of the dwarf at the last apocenter are listed in Table 2.

Table 2 Properties of the simulated dwarfs at the last apocenter

Orbit	r_{max} [kpc]	V_{max} [km/s]	$M(< r_{max})$ [10^7 $M_\odot$]	c/a	V/σ	β
O1	0.57	12.5	1.50	0.66	0.62	0.47
O2	0.25	7.7	0.27	0.96	0.11	0.04
O3	1.47	18.1	9.56	0.20	1.80	0.51
O4	0.23	7.2	0.22	0.96	0.07	0.10
O5	0.98	16.0	4.61	0.36	1.25	0.54
O6	0.90	15.3	3.79	0.45	0.86	0.56
O7	0.59	12.2	1.48	0.55	0.71	0.47

3 Conclusions

The tracks of the dwarf galaxy properties as a function of the integrated tidal force are remarkably similar. In spite of different size and eccentricity of the orbits the evolution seems to be controlled almost entirely by the amount of tidal force experienced by the dwarf. The similarity is particularly striking in the case of two pairs of orbits, O2-O4 and O1-O7. Although the orbital parameters in each pair are very different (see Table 1) the dwarfs experience a very similar integrated tidal force and all their properties at the last apocenter are also almost identical. A slight departure from the trend set by the orbits O2-O4 and O1-O7 is seen only in the case of V_{max} for orbits O5-O6 with the largest pericenter.

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