Tidal evolution of disky dwarf galaxies: prograde versus retrograde orbits

Ewa L. Łokas[1] and Marcin Semczuk[2]

1. Nicolaus Copernicus Astronomical Center, Bartycka 18, 00–716 Warszawa, Poland
2. Astronomical Observatory of the Jagiellonian University, Orla 171, 30–244 Kraków, Poland

The formation of dwarf spheroidal galaxies in the Local Group from disky progenitors via tidal interaction with a bigger host is one of the most promising scenarios of their origin. Using N-body simulations we study the process by following the evolution of a disky dwarf orbiting a Milky Way-like host. We focus on the effect of the orientation of the dwarf galaxy disk's angular momentum with respect to the orbital one. We find a strong dependence of the efficiency of the transformation from a disk to a spheroid on the disk orientation. The effect is strongest for the exactly prograde and weakest for the exactly retrograde orbit. In the prograde case the stellar component forms a strong bar and remains prolate until the end of the evolution, while its rotation is very quickly replaced by random motions of the stars. In the retrograde case the dwarf remains oblate, does not form a bar and loses rotation very slowly. Our results suggest that resonant effects are the most important mechanism underlying the evolution while tidal shocking plays only a minor role.

1 Introduction

The formation of dwarf spheroidal (dSph) galaxies in the Local Group via the tidal interaction of their disky progenitors with more massive hosts like the Milky Way is one of the most promising scenarios for their origin (Mayer et al., 2001). It explains the morphology-density relation observed among the dwarfs of the Local Group and accounts for the non-sphericity of the dSph objects. The efficiency of the mechanism and its observational predictions have been investigated in detail by Klimentowski et al. (2009), Kazantzidis et al. (2011) and Łokas et al. (2011, 2012). These studies explored the dependence of the process on a large number of orbital and structural parameters of the dwarf.

One such parameter expected to have a strong impact on the evolution is the inclination between the angular momentum of the dwarf galaxy disk and its orbital angular momentum. However, in the studies mentioned above only a narrow range of inclinations were studied in detail, namely those with values $i = 0°$, $45°$ and $90°$. Because of this range, and the way the properties of the dwarf were measured, no clear evidence for the dependence on this parameter was found.

In this paper we report preliminary results of a new study aimed at clarifying this issue. For this purpose we performed three simulations of tidal evolution of a dwarf galaxy with disk inclinations $i = 0°$ (exactly prograde), $90°$ (intermediate) and $180°$ (exactly retrograde). We also measured the properties of the dwarf galaxy in a different way that enables clear comparisons. We find a strong dependence of the evolution on the initial inclination of the disk.

2 The simulations

We simulated the interaction between the dwarf galaxy and the host using two live, two-component galaxy models. The simulation setup was similar to that in Łokas et al. (2014). Our dwarf had a standard NFW (Navarro et al., 1997) dark matter halo of mass $M_{\rm h} = 10^9$ M$_\odot$ and a concentration parameter $c = 20$. Its disk had a mass $M_{\rm d} = 2 \times 10^7$ M$_\odot$, an exponential scale-length $R_{\rm d} = 0.41$ kpc and a thickness $z_{\rm d} = 0.2\ R_{\rm d}$. The host galaxy had the properties similar to the Milky Way model MWb of Widrow & Dubinski (2005). It had a dark matter halo of mass $M_{\rm H} = 7.7 \times 10^{11}$ M$_\odot$ and concentration $c = 27$ while its disk had a mass $M_{\rm D} = 3.4 \times 10^{10}$ M$_\odot$, a length-scale $R_{\rm D} = 2.82$ kpc and a thickness $z_{\rm D} = 0.44$ kpc. We neglect other structural parameters of the Milky Way, like the bulge, the thin/thick disk or a bar.

The numerical realizations of the two galaxies were generated by the procedures described in Widrow & Dubinski (2005) and Widrow et al. (2008). Each object was modeled with 2×10^5 particles per component (8×10^5 particles in total). The evolution of the system was followed with the GADGET-2 N-body code (Springel et al. 2001; Springel 2005) adopting gravitational softening scales of $\epsilon_{\rm d} = 0.02$ kpc and $\epsilon_{\rm h} = 0.06$ kpc for the dwarf's disk and halo and $\epsilon_{\rm D} = 0.05$ kpc and $\epsilon_{\rm H} = 2$ kpc for the Milky Way, respectively. The simulation lasted for 10 Gyr and outputs were saved every 0.05 Gyr.

The initial configuration for all three simulations was such that the dwarf's orbit and the Milky Way disk were in the XY plane of the simulation box. The dwarf galaxy was initially placed at the apocenter $(X, Y, Z) = (-120, 0, 0)$ kpc of the orbit (which had a pericenter of 25 kpc) with a systemic velocity towards the negative Y axis, so that the orbital angular momentum is pointing towards the positive Z of the simulation box. The orientation of the (unit) angular momentum of the dwarf was $(L_X, L_Y, L_Z) = (0, 0, 1)$ for the exactly prograde case ($i = 0°$), $(0, 0, -1)$ for the exactly retrograde case ($i = 180°$) and $(0, -1, 0)$ for the intermediate case ($i = 90°$).

3 Evolution of the kinematics and shape

To quantify the kinematic evolution of the dwarf galaxy in each of the three simulations, for each output we selected stars within the radius of 0.5 kpc and determined the principal axes of the stellar component from the inertia tensor. Next, we rotated the stars so that the x coordinate was along the longest, the y along the intermediate, and z along the shortest principal axis. A standard spherical coordinate system was then introduced and we measured the kinematics using these coordinates.

The dominant component of the streaming motion of the stars is always around the shortest axis. We measured the mean rotation around this axis for stars within 0.5 kpc for all outputs of the three simulations. The results are shown in the upper panel of Figure 1. The middle panel of the Figure shows the measurements of the 1D velocity dispersion which is the average of dispersions along the three spherical coordinates. In the lower panel we plot the anisotropy parameter β of the stars.

In each panel the solid, dashed and dotted line shows the results for the prograde ($i = 0°$), intermediate ($i = 90°$) and retrograde ($i = 180°$) inclination of the disk. Abrupt changes of velocity and dispersion take place at pericenter passages that occur at $t = 1.2, 3.3, 5.5, 7.6, 9.7$ Gyr from the start of the simulation. We find a systematic trend in the behaviour of both the rotation and dispersion values among the three simulations: in the prograde case the rotation velocity decreases and the dispersion

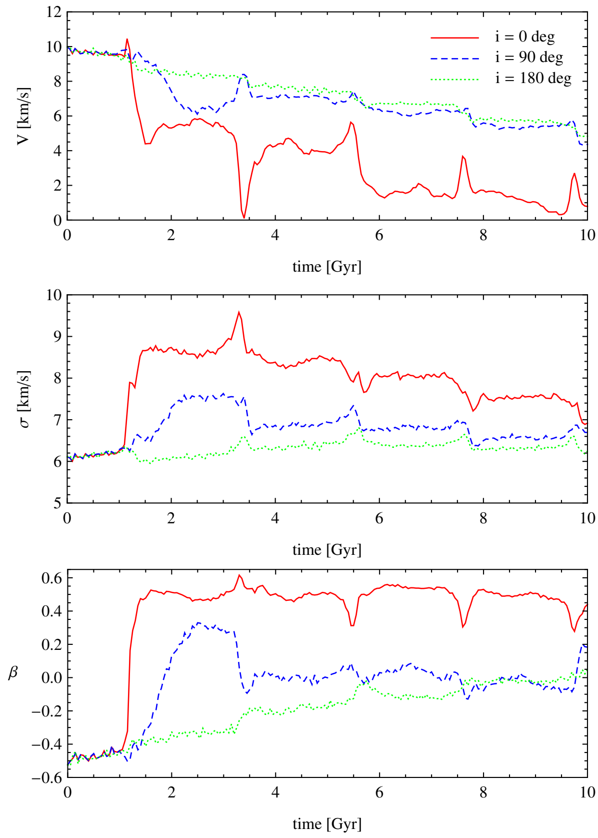

Fig. 1: Evolution of the kinematic properties of the dwarf galaxy in time. The upper panel shows the mean rotation velocity V, the middle panel the average 1D velocity dispersion σ and the lower panel the anisotropy parameter β of the stars within 0.5 kpc. In each panel the solid, dashed and dotted line corresponds to the results for the prograde ($i = 0°$), intermediate ($i = 90°$) and retrograde ($i = 180°$) inclination of the disk.

grows most significantly in time and in the retrograde case the changes are the smallest. Therefore the transition from the ordered to the random motion is strongest in the prograde case. In addition, in this case the random motions are dominated by the radial velocity dispersion, as demonstrated by the highest values of anisotropy of stellar orbits.

We also determined the shape of the stellar component from the same subsamples of stars. The results in terms of the intermediate to longest b/a and the shortest to longest c/a axis ratio are shown in the upper and lower panel of Figure 2, respectively. To further illustrate the evolution of the shape, in Figure 3 we plot the triaxiality parameter $T = [1 - (b/a)^2]/[1 - (c/a)^2]$ (upper panel) and the bar mode A_2 of the Fourier decomposition of the stellar component projected along the shortest axis (lower panel). As before, the solid, dashed and dotted line shows the results for the prograde, intermediate and retrograde orientation of the disk. Also for these quantities most significant changes occur at pericenter passages.

While the evolution of c/a in time is similar in all cases, the variation of b/a in time

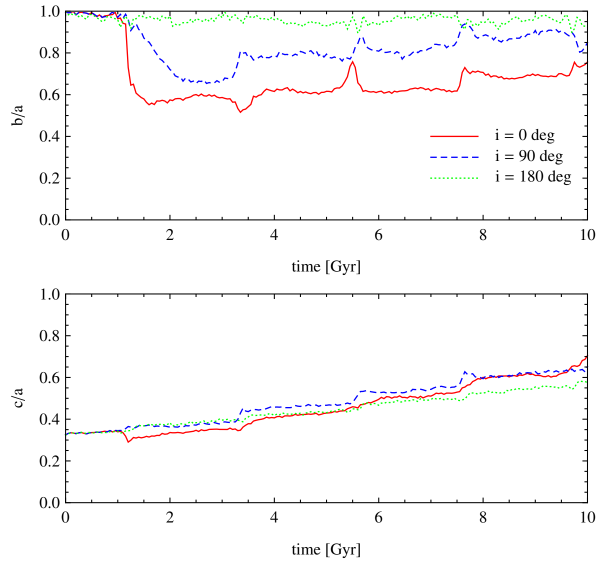

Fig. 2: Evolution of the shape of the dwarf galaxy in time in terms of the axis ratios of the stellar component. The upper panel shows the intermediate to longest (b/a) and the lower one the shortest to longest (c/a) axis ratio of stars within radius 0.5 kpc. In each panel the solid, dashed and dotted line corresponds to the results for the prograde ($i = 0°$), intermediate ($i = 90°$) and retrograde ($i = 180°$) inclination of the disk.

is very different for the prograde, intermediate and retrograde orientation of the disk. In the prograde case the shape is always prolate ($T > 2/3$), in the intermediate case it is triaxial ($1/3 < T < 2/3$) and in the retrograde case it remains oblate ($T < 1/3$), like the initial disk. In the retrograde case the dwarf does not undergo any significant morphological transformation, it remains disky, only the disk thickens with time due to tidal shocks at pericenter passages. In the two other cases, the dwarf forms a bar at the first pericenter passage, but the bar is much stronger in the exactly prograde case, as confirmed by the highest A_2 values for this case at all times.

4 Discussion

We presented the results of three simulations of tidal evolution of initially disky dwarf galaxies orbiting the Milky Way-like host. In all cases the dwarf was placed on a typical, eccentric orbit and its evolution was followed for 10 Gyr. The three configurations differed only by the initial inclination of the dwarf galaxy disk's angular momentum with respect to the orbital angular momentum. We find very significant differences between the properties of the evolving dwarf for the three inclinations and they seem to scale monotonically with the inclination angle.

The evolution of the dwarf is strongest in the case of prograde inclination of the disk. In this configuration a strong bar forms at the first pericenter passage and although the shape of the stellar component becomes more spherical in time, it remains prolate until the end of the simulation. The morphological transformation is accompanied by strong modification of the dwarf's kinematics: at the first pericenter the rotation is significantly reduced and replaced by random motions of the stars,

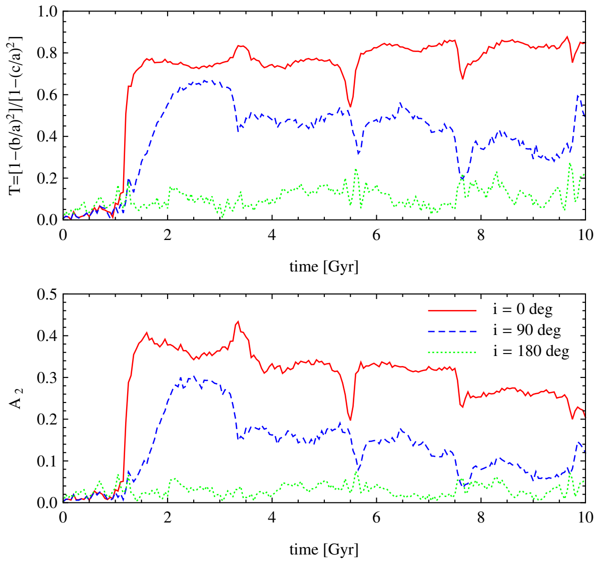

Fig. 3: Evolution of the shape of the dwarf galaxy in time in terms of the triaxiality parameter T (upper panel) and the bar mode A_2 (lower panel) of the stellar component. In each panel the solid, dashed and dotted line corresponds to the results for the prograde ($i = 0°$), intermediate ($i = 90°$) and retrograde ($i = 180°$) inclination of the disk.

mostly in the radial direction as is characteristic of the bar. The rotation continues to decrease in time so that almost no streaming motion remains at the end of the evolution. On the other hand, the decrease of the velocity dispersion at later times reflects the mass loss due to tidal stripping.

In the intermediate case, that of perpendicular orientation of the disk with respect to the orbit, the changes are qualitatively similar, but less pronounced. A bar also forms at the first pericenter passage, but it is more triaxial than prolate. The decrease of rotation velocity and the increase of velocity dispersion are also weaker effects. In the exactly retrograde case no significant evolution is seen: the dwarf's stellar component does not form a bar and remains disky. The disk thickens in time and rotation is slightly diminished.

The results presented here suggest that the most important mechanism underlying the evolution of disky dwarfs is of resonant nature since the effect is strongest when the dwarf's angular momentum is aligned with the orbital one. We may refer to it as 'resonant stirring' in analogy to the 'resonant stripping' mechanism found to increase the mass loss in similar configurations (D'Onghia et al., 2009, 2010). We plan to investigate the details of the process in future work.

Acknowledgements. This work was supported in part by PL-Grid Infrastructure, the Polish National Science Centre under grant 2013/10/A/ST9/00023, by US National Science Foundation Grant No. PHYS-1066293 and the hospitality of the Aspen Center for Physics. MS acknowledges the summer student program of the Copernicus Center. We thank L. Widrow for providing procedures to generate N-body models of galaxies for initial conditions.

References

D'Onghia, E., Besla, G., Cox, T. J., Hernquist, L., *Resonant stripping as the origin of dwarf spheroidal galaxies*, *Nature* **460**, 605 (2009)

D'Onghia, E., Vogelsberger, M., Faucher-Giguere, C. A., Hernquist, L., *Quasi-resonant Theory of Tidal Interactions*, *ApJ* **725**, 353 (2010)

Kazantzidis, S., et al., *On the efficiency of the tidal stirring mechanism for the origin of dwarf spheroidals: dependence on the orbital and structural parameters of the progenitor disky dwarfs*, *ApJ* **726**, 98 (2011)

Klimentowski, J., et al., *Tidal evolution of disky dwarf galaxies in the Milky Way potential: the formation of dwarf spheroidals*, *MNRAS* **397**, 2015 (2009)

Łokas, E. L., Kazantzidis, S., Mayer, L., *Evolutionary tracks of tidally stirred disky dwarf galaxies*, *ApJ* **739**, 46 (2011)

Łokas, E. L., et al., *The shapes of Milky Way satellites: looking for signatures of tidal stirring*, *ApJ* **751**, 61 (2012)

Łokas, E. L., et al., *Adventures of a tidally induced bar*, MNRAS **445**, 1339 (2014)

Mayer, L., et al., *The Metamorphosis of Tidally Stirred Dwarf Galaxies*, *ApJ* **559**, 754 (2001)

Navarro, J. F., Frenk, C. S., White, S. D. M., *A universal density profile from hierarchical clustering*, *ApJ* **490**, 493 (1997)

Springel, V., *The cosmological simulation code GADGET-2*, *MNRAS* **364**, 1105 (2005)

Springel, V., Yoshida, N., White, S. D. M., *GADGET: A code for collisionless and gasdynamical cosmological simulations*, *New Astronomy* **6**, 79 (2001)

Widrow, L. M., Dubinski, J., *Equilibrium disk-bulge-halo models for the Milky Way and Andromeda galaxies*, *ApJ* **631**, 838 (2005)

Widrow, L. M., Pym, B., Dubinski, J., *Dynamical blueprints for galaxies*, *ApJ* **679**, 1239 (2008)