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The major merger origin of the Andromeda II kinematics

Ivana Ebrová, Ewa L. Łokas, Sylvain Fouquet and Andrés del Pino

Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences,
Bartycka 18, 00-716 Warsaw, Poland

Abstract. Prolate rotation (i.e. rotation around the long axis) has been reported for two Local Group dwarf galaxies: Andromeda II, a dwarf spheroidal satellite of M31, and Phoenix, a transition type dwarf galaxy. The prolate rotation may be an exceptional indicator of a past major merger between dwarf galaxies. We showed that this type of rotation cannot be obtained in the tidal stirring scenario, in which the satellite is transformed from disky to spheroidal by tidal forces of the host galaxy. However, we successfully reproduced the observed Andromeda II kinematics in controlled, self-consistent simulations of mergers between equal-mass disky dwarf galaxies on a radial or close-to-radial orbit. In simulations including gas dynamics, star formation and ram pressure stripping, we are able to reproduce more of the observed properties of Andromeda II: the unusual rotation, the bimodal star formation history and the spatial distribution of the two stellar populations, as well as the lack of gas. We support this scenario by demonstrating the merger origin of prolate rotation in the cosmological context for sufficiently resolved galaxies in the Illustris large-scale cosmological hydrodynamical simulation.

Keywords. galaxies: dwarf, (galaxies:) Local Group, galaxies: individual (Andromeda II), galaxies: kinematics and dynamics, galaxies: interactions, galaxies: evolution, galaxies: peculiar, methods: *N*-body simulations

1. Introduction

Andromeda II (And II) dwarf spheroidal galaxy (dSph) is a relatively luminous satellite of M31. It has a stellar mass of $\sim 10^7\,\mathrm{M}_\odot$, a half-mass radius 1 kpc, and ellipticity 0.1–0.2 (e.g., McConnachie & Irwin 2006 and del Pino *et al.* 2017). Unlike most dSphs, And II contains not only old stars (> 10 Gyr) but also significant intermediate-age population. The two stellar populations differ in age, metallicity, and density profiles (McConnachie *et al.* 2007). Ho *et al.* (2012) detected prolate rotation (also known as minor-axis rotation): the rotation around the major axis of the galaxy, i.e. the angle measured between photometric and kinematic axes is close to 90 deg. Later, the prolate rotation was also reported in Phoenix, a transition-type dwarf (i.e., a galaxy that displays intermediate properties between a dwarf irregular and a dwarf spheroidal; Kacharov *et al.* 2017). And II, and possibly Phoenix, could be exceptional examples of remnants of past major mergers of dwarf galaxies.

A classical scenario known to lead to the formation of dSph galaxies is based on a long-term interaction of the dwarfs with their host galaxies such as the Milky Way or M31. Initially disky dwarf satellites are transformed to gasless spheroidals due to tidal forces, dynamical friction and ram-pressure stripping (e.g., Mayer *et al.* 2001). In Łokas *et al.* (2014) and Ebrová & Łokas (2015), we argued that tidal interaction is able to remove the initial disk rotation as it transforms to a bar and then a spheroid, but cannot induce any significant prolate rotation (see also Łokas *et al.* 2015). Here we review how the observed properties of And II, and prolate rotation in general, can be reproduced via mergers of galaxies.

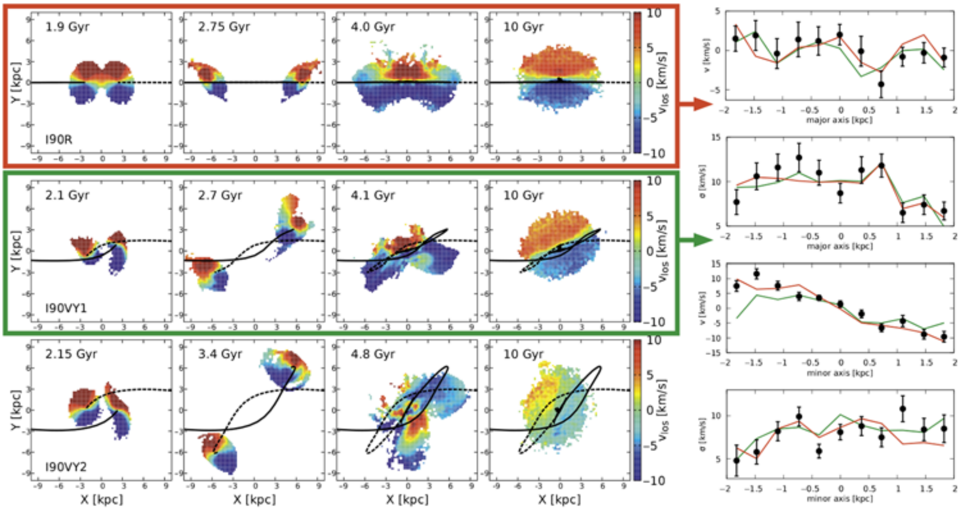

Figure 1. Left: Genesis of prolate rotation in three N-body simulations of equal-mass mergers of disky dwarf galaxies with different initial orbital angular momenta of the colliding galaxies. Black lines indicate the orbits followed by the dwarfs up to the given time. Each panel shows the area of 20×20 kpc. Right: Comparison of mean line-of-sight velocity and velocity dispersion along the axes as observed in And II (black points: data from Ho *et al.* 2012) and produced in the simulations: the radial merger (red; I90R, top row on the left) and the slightly non-radial merger (green; I90VY1, middle row on the left). Simulated data are computed along the appropriate line of sight for about 500 stellar particles, mimicking the spatial coverage of the observations. The Figure is based on Figs. 3 and 15 from Ebrová & Łokas (2015).

2. The merger origin of prolate rotation

Using Gadget-2 (Springel 2005), we performed a series of collisionless self-consistent N-body simulations of dwarf mergers with different initial conditions leading to the formation of a dSph with prolate rotation. Both merger progenitors had disk mass of $2 \times 10^7\,M_\odot$ (10^6 particles) and a Navarro-Frenk-White dark halo with mass of $10^9\,M_\odot$ (10^6 particles). In the remnants of the radial mergers, the amount of rotation is controlled by the inclination of the disks with respect to the collision axis and all the radial mergers with disk inclinations 60, 90, and 120 deg reproduce the observed And II kinematics. The non-radial orbits lead to prolate rotation if the orbital angular momentum is initially not much larger than the intrinsic angular momentum of the progenitor disks. The left part of Fig. 1 shows snapshots from three simulations with the same initial disk inclination 90 deg but with a different initial ratio of the tangential to radial velocity, from top to bottom: 0, 0.125, and 0.25. The remnants of the most non-radial merger have rotation too low to account for And II but the other two reproduce the observed And II kinematics (the right side of Fig. 1) as well as the elliptical shape. The orbital structure of all the simulated merger remnants is dominated by box orbits in the center and long-axis tubes in the outer parts. For more details see Ebrová & Łokas (2015).

In a follow-up study, we performed a two-stage hydrodynamical simulation including cooling, star formation, and feedback. An equal-mass radial merger of disky dwarfs with initial gas fraction of 0.7 was followed by a ram-pressure stripping of the merger remnant in the hot gaseous halo of M31. Such a simulation successfully reproduces the star-formation history of And II, see Fig. 2, as well as other observed properties: the magnitude of the prolate rotation, the mass and shape, the lack of gas, and the spatial distribution of the two stellar populations. For more details see Fouquet *et al.* (2017).

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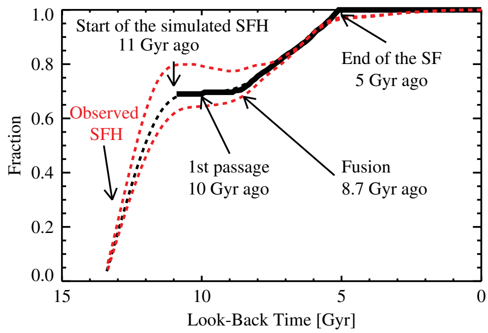

Figure 2. Simulated star formation history of And II (thick black line) compared to the observed one (dashed lines; del Pino *et al.* 2017). Red lines show the observational uncertainties. The main stages of the major merger are indicated. The Figure is adapted from Fig. 7 in Fouquet *et al.* (2017).

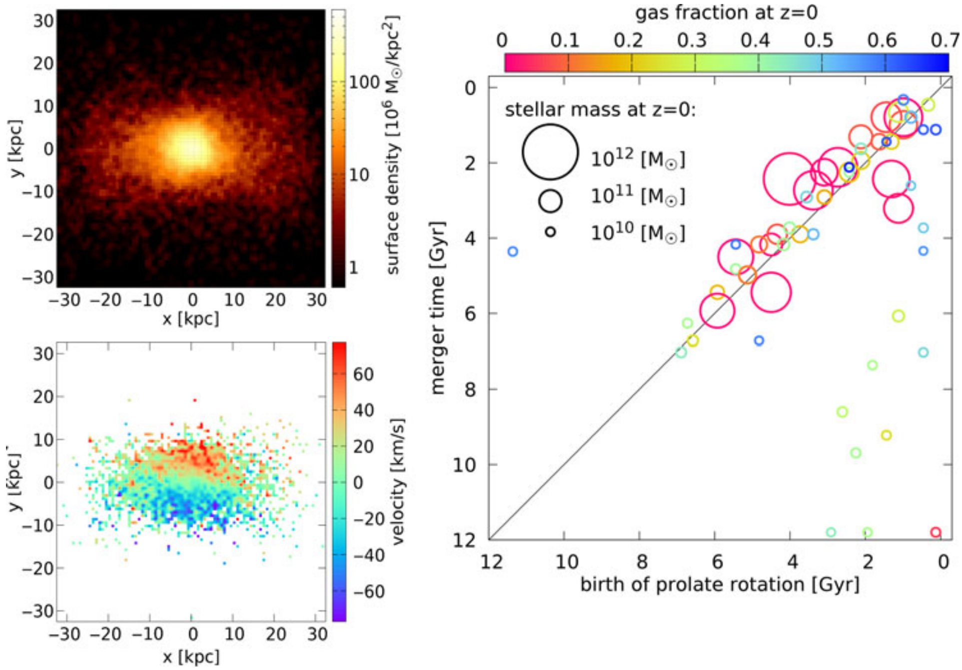

Figure 3. Left: Example of a galaxy with prolate rotation from the final snapshot of the Illustris-1 run. The galaxy has stellar mass $\sim 10^6$ M$_\odot$ and it maintains prolate rotation since it underwent a major merger 4.17 Gyr ago. Right: Correlation of the look-back time of the last significant merger (i.e. stellar mass ratio 0.1 or greater) with the look-back time at which prolate rotation emerged for 59 prolate rotators from Illustris. Circle sizes are proportional to the stellar mass and colors reflect the gas fraction at the last snapshot. The Figure is based on Figs. 2 and 7 from Ebrová & Łokas (2017).

We explored the origin of the prolate rotation using publicly available data from the Illustris large-scale hydrodynamical cosmological simulation (AREPO moving-mesh code, 106.3 Mpc box size, 6×10^9 initial hydrodynamic cells and 6×10^9 dark matter particles; Nelson *et al.* 2015, Vogelsberger *et al.* 2014, Rodriguez-Gomez *et al.* 2015). From the last snapshot, we selected 59 well resolved galaxies with well-established prolate rotation (see the left part of Fig. 3 for one example). These prolate rotators are more abundant

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among massive galaxies just as reported for the observed galaxies (Tsatsi *et al.* 2017, Krajnović *et al.* 2018). The birth of prolate rotation strongly correlates with the last significant merger (Fig. 3 on the right). The mergers leading to prolate rotation have a wide range of initial conditions but they are slightly more radial and have higher mass ratios and more recent merger times than mergers of the comparison sample. About half of Illustris prolate rotators are created in gas-rich mergers. For more details see Ebrová & Łokas (2017).

3. Conclusions

We demonstrated that prolate rotation, detected in And II and Phoenix dwarf galaxies, which cannot be reproduced in the scenario of disky dwarfs interacting with the host galaxy, can be generated in a major merger of two disky dwarfs on a radial or close-to-radial orbit. The observed And II kinematics, the star formation history, the spatial distribution of the two stellar populations, and the lack of gas is best explained in a simulation of a gas-rich merger of two disky dwarfs about 9 Gyr ago followed by ram-pressure stripping caused by a close interaction with M31 about 5 Gyr ago. We support this scenario by demonstrating the merger origin of prolate rotation in the cosmological context in the Illustris simulation.

Acknowledgements

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