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Origin of stellar prolate rotation in a cosmologically simulated faint dwarf galaxy

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ABSTRACT
Stellar prolate rotation in dwarf galaxies is rather uncommon, with only two known galaxies in the Local Group showing such feature (Phoenix and And II). Cosmological simulations show that in massive early-type galaxies stellar prolate rotation likely arises from major mergers. However, the origin of such kinematics in the dwarf galaxies regime has only been explored using idealized simulations. Here, we made use of hydrodynamical cosmological simulations of dwarfs galaxies with stellar mass between $3 \times 10^5$ and $5 \times 10^8 \, M_\odot$ to explore the formation of prolate rotators. Out of 27 dwarfs, only one system showed clear rotation around the major axis, whose culprit is a major merger at $z = 1.64$, which caused the transition from an oblate to a prolate configuration. Interestingly, this galaxy displays a steep metallicity gradient, reminiscent of the one measured in Phoenix and And II: this is the outcome of the merger event that dynamically heats old, metal-poor stars, and of the centrally concentrated residual star formation. Major mergers in dwarf galaxies offer a viable explanation for the formation of such peculiar systems, characterized by steep metallicity gradients and prolate rotation.

Key words: galaxies: formation – Local Group.

1 INTRODUCTION
Kinematic anomalies, such as misaligned rotation axes, counter-rotating cores, and sub-structures, can be tell-tales of the occurrence of important, violent events in the life of a galaxy, e.g. mergers (e.g. Cox et al. 2006; Shapiro et al. 2008; Barrera-Ballesteros et al. 2015; Ebrová, Łokas & Eliášek 2021b; Nevin et al. 2021).

A characteristic of special interest is the presence of stellar prolate rotation, i.e. when the angular momentum of the stellar component is aligned with its major axis. Prolate rotation seems to be fairly common in massive early-type galaxies (ETGs), with its frequency increasing with stellar mass, as seen in observations (see e.g. Tsatsi et al. 2017; Krajnović et al. 2018, and references therein) and cosmological simulations such as Illustris and Magneticum Pathfinder (see Ebrová & Łokas 2017, hereafter EL17; Schulze et al. 2018). Both simulations and observations indicate mergers as the culprit for stellar prolate rotation. Theoretical works suggest that, while not all mergers do lead to prolate rotation, its appearance strongly correlates with the time of the last major merger (EL17), and is more likely to be found in systems that undergo a larger number of gas-poor mergers (Lagos et al. 2020). In the observational counterpart, Ebrová et al. (2021a) found signs of recent interactions (i.e. tidal tails, shells, asymmetric stellar haloes, etc.) in all prolate ETGs analysed in their study.

Even though in a $\Lambda$ cold dark matter (CMD) context merger events are expected to occur fairly frequently even at low galaxy masses (Deason, Wetzel & Garrison-Kimmel 2014; Rodríguez-Gomez et al. 2015; Wetzel, Deason & Garrison-Kimmel 2015; Martin et al. 2021), so far, a direct detection of such events on the scale of dwarf galaxies is limited to Large Magellanic Cloud-mass objects (Martínez-Delgado et al. 2012; Prinson et al. 2017; Annibali et al. 2019; Carlin et al. 2019). Therefore, it is particularly intriguing to understand whether indeed the presence of features such as prolate rotation can be interpreted as an indirect but secure sign of the occurrence of past mergers.

Among the population of Local Group (LG) dwarf galaxies, only two systems exhibit prolate rotation: a satellite of M31, And II (Ho et al. 2012), and the Phoenix transition type dwarf (Kacharov et al. 2017), found at 400 kpc from the Milky Way and likely on its first approach. In both cases, mergers have been invoked to explain such an anomalous rotation, also given the presence of other curious characteristics, such as a stellar stream or misaligned rotating components in And II (Amorisco, Evans & van de Ven 2014; Del Pino et al. 2017) and the presence of a young stellar component tilted of 90° with respect to the main body in Phoenix (Hidalgo et al. 2009; Battaglia et al. 2012).

To the best of our knowledge, in the mass range of LG dwarf galaxies, only idealized simulations have been used to explore the
occurrence of prolate rotation. Lokas et al. (2014) used idealized N-body simulations and proposed an evolutionary model for And II that involved the merger between two equal-mass discy dwarf galaxies, placed in a radial orbit towards each other and with a specific inclination of the discs angular momenta. Ebrová & Lokas (2015) expanded this analysis to five collisionless simulations, exploring also non-radial orbits and three inclinations, showing that prolate rotation does not need radial orbits to arise and can also be produced in mergers with different relative orientation of the discs. However, equal-mass mergers between two dwarf galaxies are probably not a common occurrence (see, for example, recent simulation results by Di Cintio et al. 2021) and in general observations suggest that dwarf galaxies at those stellar masses are typically not highly rotating (Wheeler et al. 2017; Kirby et al. 2020).

In this work, we perform a search for stellar prolate rotation in a set of simulated dwarf galaxies of stellar masses akin to those of And II and Phoenix, using the hydrodynamical cosmological simulations from Revaz & Jablonka (2018), hereafter RJ18. Our aim is not to specifically reproduce the characteristics of either system, but rather to understand whether prolate rotation can naturally occur under more realistic configurations for the progenitors, both in terms of their structure/internal kinematics and orbital configuration, i.e. by using fully cosmological initial conditions rather than idealized ones. In Section 2, we discuss the simulations analysed; in Section 3, we perform the search for prolate rotation, assess its significance and explain its origin, and in Section 4, we look at the effect this merger had in setting the system’s metallicity gradient. We present a summary in Section 5.

2 SIMULATIONS

We analysed 27 dwarf galaxies from the high-resolution, zoom-in cosmological hydrodynamical simulations presented in RJ18. The spatial resolution of these simulations has been set to properly resolve dwarf spheroidal galaxies, with the software length for the gas and dark matter (DM) particles being 10 and 50 pc h$^{-1}$, respectively. The simulated galaxies span more than 3 dex in stellar mass from $3 \times 10^{6}$ to $5 \times 10^{9}$ M$_{\odot}$, well representing LG classical dwarfs, of which they have been shown to correctly reproduce many global relations linking galaxy mass, luminosity, and mean metallicity as well as the detailed chemical patterns derived from the stellar abundance ratios (RJ18). The simulations have been run using the code GEAR (Revaz et al. 2012), a fully parallel code based on GADGET-2 (Springel 2005). Initial conditions assume a Planck cosmology (Alves et al. 2016). Gas cooling is done through the GRACKLE cooling library (Smith et al. 2017), while gas heating is included via a redshift-dependent ultra violet background and supernovae (SNe) thermal feedback. Gas, stellar, and DM particles have an initial mass of 4096, 1024, and 22 462 M$_{\odot}$ h$^{-1}$, respectively. Each star particle is formed assuming a Kroupa (2001) initial mass function, and is stochastically sampled using the random discrete scheme described in Revaz et al. (2016), in order to set the number and time delay of the Type Ia and Type II SNe. These SNe inject 10 per cent of their energy into the interstellar medium via thermal blast-wave feedback (Stinson et al. 2006), while also enriching neighbour gas particles. Chemical mixing is allowed by employing a smooth metallicity scheme (Wiersma et al. 2009).

For a detailed description of the characteristics of the runs, we refer the reader to Revaz et al. (2012, 2016) and RJ18.

### Table 1

Properties of $\Omega_0 H_0$ at $z = 0$ (left) and at $z = 1.78$ (middle), corresponding to its main progenitor just before the merger analysed; properties of the accreting satellite at $z = 1.78$ (right). We include the virial mass $M_{\text{vir}}$, the stellar mass $M_*$, the total gas mass $M_{\text{gas}}$, the ratio between the angular momentum of the stellar component parallel to the major axis and the total angular momentum $(L_{\text{Major}}/L_{\text{toal}})$, the rotation velocity at 2 kpc divided by the 3D velocity dispersion $\sigma_{3D}^2 = \sum_i \sigma_i^2/3$, the axis ratios $b/a$ and $c/a$, and the 3D and projected stellar half-mass radii $r_{1/2}$ and $R_{1/2}$.

| Host $z = 0$ | Host $z = 1.78$ | Satellite $z = 1.78$ |
|--------------|-----------------|----------------------|
| $M_{\text{vir}}/M_*$ | $2.8 \times 10^9$ | $1.6 \times 10^9$ | $3.4 \times 10^8$ |
| $M_*/M_{\text{gas}}$ | $1.4 \times 10^7$ | $6.5 \times 10^6$ | $2.4 \times 10^5$ |
| $M_{\text{gas}}/M_{\text{vir}}$ | $2.3 \times 10^1$ | $4.0 \times 10^2$ | $9.1 \times 10^4$ |
| $(L_{\text{Major}}/L_{\text{toal}})^2$ | 0.780 | 0.040 | 0.004 |
| $v_{\text{rot}}^2/\sigma_{3D}^2$ | 0.19 | 0.30 | 0.33 |
| $b/a$ | 0.76 | 0.64 | 0.68 |
| $c/a$ | 0.70 | 0.49 | 0.51 |
| $r_{1/2}$/kpc | 0.70 | 0.64 | 0.62 |
| $R_{1/2}$/kpc | 0.57 | 0.48 | 0.42 |

3 PROLATE ROTATION

3.1 Identification

We have systematically analysed the set of 27 simulated dwarf galaxies described above, searching for prolate rotation in their stellar components at all redshifts. In order to identify the prolate nature of a simulated galaxy, we have compared the angle ($\theta$) between the stellar angular momentum vector and the orientation of the principal axes of the ellipsoid that best represents the 3D stellar distribution of a specific galaxy. By definition, in a prolate rotating galaxy, the major axis and the angular momentum should be parallel (i.e. $\cos \theta \sim 1$). We consider a system to be clearly prolate rotating when $\cos \theta > 0.9$ for more than 2 consecutive Gyr.

In order to compute the principal axes of the stellar component, we have implemented an iterative method that computes the inertia tensor of the stellar distribution in a pre-defined spherical aperture of 4 kpc from the centre of the galaxy. The eigenvalues of this matrix can then be easily related to the principal axes of an ellipsoid.

With this method, we identified only one system that shows clear signs of prolate rotation. We refer to it as $\Omega_0 H_0$, where the ID is the same as in RJ18. At $z = 0$, this galaxy presents a stellar mass of $1.37 \times 10^9$ M$_{\odot}$ and a 3D stellar half-mass radius of 0.70 kpc. The 3D average rotation curve, up to 4 kpc, increases linearly with radius, with the average slope of the rotational velocity being $v_{\text{rot}}/dr = 0.88 \pm 0.12$ km s$^{-1}$ kpc$^{-1}$, where $r$ indicates the distance to the major axis. Table 1 summarizes the main characteristics of this system at different redshifts.

Fig. 1, top panel, shows the principal axes orientation with respect to the stellar angular momentum as a function of look-back time. It is evident that galaxy $\Omega_0 H_0$ suffers a transformation at $\sim 10$ Gyr, which completely changes the orientation of its stellar angular momentum vector, from being perpendicular to the major axis ($\cos \theta = 0$) to being parallel ($\cos \theta \sim 1$). The transformation appears to become complete at a look-back time of $\sim 6.5$ Gyr and remains stable afterwards until $z = 0$.

We have also checked that our galaxy fulfills the selection criteria used by EL17, i.e. that the fraction of angular momentum around the major axis, $L_{\text{Major}}$ is larger than 0.5 of the total angular momentum.

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1We have tested different apertures and the results are consistent.
to each ‘star’; each of the components of the velocity vector must arise from a non-rotating distribution.

We have also compared the values of \((L_{\text{maj}}/L_{\text{T}})^2\) of h048 with one of the mocks. We have chosen two apertures in which to measure this quantity: inside the 3D half-mass radius (0.70 kpc), and between the half mass radius and 4 kpc. The obtained values for h048 are 0.769 and 0.751 for the two regions, respectively. Only 0.9 per cent of the mocks have a ratio \((L_{\text{maj}}/L_{\text{T}})^2\) as large as h048, or larger, in both regions at the same time. We conclude then that the signal detected has a low probability to appear in a non-rotating system.

3.3 Origin

In order to investigate the causal link between the appearance of the prolate rotation and the main events in the life of galaxy h048, we explore its mass accretion history. We constructed halo catalogues for all the snapshots in the simulation using the Amiga Halo Finder (Gill, Kneb & Gibson 2004; Knollmann & Knebe 2009) and merger trees using the freely available code MetroC++\(^2\). In the bottom panel of Fig. 1, we show the orbits of several subhaloes that merged with the main progenitor of the galaxy (note that only haloes with more than 500 particles are considered for the construction of the merger trees). We also show the star formation history (SFH) of the main galaxy and the growth of its DM halo by means of its virial radius. It can be clearly seen that most of the mass assembly of h048 occurs in the first Gyrs, having acquired half of its final, redshift 0 mass about 10.5 Gyr ago. In this timeframe, the galaxy undergoes several mergers and its SF is at its peak, due to the infalling material as well as to the available star forming gas.

After the first \(~2\) Gyr, the number of mergers is reduced, and the galaxy settles up in a triaxial configuration, with a mild rotation about the 3D minor axis reaching an amplitude of 3 km s\(^{-1}\) at 1 kpc (top panels of Fig. 2, see also central column of Table 1 for a summary of the physical properties of the main progenitor).

Around 9.5 Gyr ago, the galaxy undergoes a massive accretion event with a luminous sub-halo with a stellar mass of \(2.4 \times 10^8\) M\(_{\odot}\) and a halo mass of \(3.4 \times 10^9\) M\(_{\odot}\), with a mass ratio of 2:10 in DM mass (see Table 1). Fig. 2 shows the projected velocity field and stellar density before the merger (top), after the merger (middle), and at redshift 0 (bottom). In these images, the dynamical transformation from an oblate to a prolate rotator can be seen, coinciding exactly with the time of such major merger event.

This accretion event does not seem to have a tangible consequence on the SFH of the host. However, there appears to be a clear correlation between the approach of the satellite and the change in the orientation of the angular momentum vector with respect to the direction of the principal axes, with the largest variations seen in correspondence to the pericentric passages. We therefore concluded that this event appears to be responsible of the prolate rotation of galaxy h048.

4 METALLICITY GRADIENT

Kacharov et al. (2017) point out that And II and Phoenix, the only LG dwarf galaxies where prolate rotation has been detected, both share a similar steep metallicity gradient, which also appears to be the steepest gradient measured in LG dwarfs. One could then ask whether this is only a consequence of the pronounced age gradient existing in both systems (see e.g. Hidalgo et al. 2009; Del Pino et al. 2017) or whether the putative massive accretion event responsible for

\(^2\)https://github.com/EdoardoCarlesi/MetroCPP.git
the prolate rotation might have played a role. In order to investigate this aspect, we look at the properties of h048.

In the top panel of Fig. 3, we show the average metallicity and age profiles of the galaxy at $z = 0$. The profiles are shown in projection, with the line of sight perpendicular to the stellar angular momentum vector, for a better comparison with the observations. The bins have been constructed in order to contain at least 200 particles and have a minimum width of 0.1 kpc in elliptical radius.

The simulated galaxy presents a strong metallicity gradient ($-0.67 \pm 0.03$ dex kpc$^{-1}$ measured within an aperture of 2 effective radii), which happens to be very similar to those of And II and Phoenix, and the metallicity gradient clearly anticorrelates with the age profile.

We then looked at the time evolution of the slope of the metallicity gradient (bottom panel of Fig. 3). It is apparent that, by the time the peak of SF has ceased, there is no metallicity gradient or only a very mild one (depending on the aperture in which it is calculated). Around the time of the main accretion event, a clear gradient is imprinted. After the merger, the gradient keeps evolving and increasing, smoothly. While the value of the gradient is somewhat dependent on the aperture, the main evolution is robust to it. We find that the merger dynamically heats the pre-existing population of stars, which move to wider orbits (compatible with the ‘outside-in’ formation scenario of Benítez-Llambay et al. 2016). The residual SF forms a population of younger metal-rich stars that are no longer spatially mixed with the old population. This duality in the stellar population is able to generate a metallicity gradient of $\sim 0.4$ dex kpc$^{-1}$ in $\sim 1$ Gyr.

After the merger, the galaxy is not completely quenched (see bottom panel of Fig. 1). We verified that the residual SF is limited to the very inner regions of the galaxy. This particular shape of the SF distribution is imprinted in the evolution of the metallicity gradient and is responsible for the smooth steepening of the metallicity profile that happens after the merger. This process is in agreement with the correlation between the SFH and the metallicity gradient found in RJ18. We conclude that while the accretion event responsible for the prolate rotation is not the only cause of the presence of a metallicity gradient, it has played a significant role in steepening it, and that it is possible that the same occurred to And II and Phoenix.

5 DISCUSSION AND SUMMARY

We performed a systematic search for prolate stellar rotation among 27 simulated dwarf galaxies from the cosmological hydrodynamical
zoom-in simulations described in RJ18. Those systems cover the stellar mass range between 3 × 10^7 and 5 × 10^8 M_☉, similar to LG dwarf galaxies. Out of those 27 galaxies, we find one prolate rotator, with a total mass of 2.8 × 10^10 M_☉ and stellar mass of 1.4 × 10^9 M_☉ at z = 0. Even though the detected velocity gradient is of low amplitude, the analysis of mock data sets suggests that it is unlikely that a velocity gradient of the same or larger amplitude would have arisen from a non-rotating system. To the best of our knowledge, this is the first time that a prolate rotating galaxy with such a small mass has been identified using non-idealized cosmological simulations.

The comparison between the merger history of h048 and the evolution of the alignment between the principal axes of the stellar body with the direction of its angular momentum vector clearly indicates that a major merger (mass ratio 2:10) is responsible for altering the internal kinematic properties of the host galaxy, changing it from an oblate to a prolate rotator. The transformation is completed around 6 Gyr ago, and the new configuration remains stable after that. This extends to a lower mass range the conclusions by EL17.

The ‘host’ and main satellite before the merger have different DM and stellar mass, and their spheroidal-like structure and low evolution of the alignment between the principal axes of the stellar body with the direction of its angular momentum vector clearly indicates that a major merger (mass ratio 2:10) is responsible for altering the internal kinematic properties of the host galaxy, changing it from an oblate to a prolate rotator. The transformation is completed around 6 Gyr ago, and the new configuration remains stable after that. This extends to a lower mass range the conclusions by EL17.

Finally, the metallicity gradient in the simulated galaxy showing prolate rotation happens to be as steep as that measured for the Phoenix and And II. The formation of this steep metallicity gradient appears to be the combined result of the merger event responsible of the prolate rotation, which pushes to larger orbits the metal-poor stars that were formed before 9.5 Gyr, and the subsequent SF, which is limited to the inner half-mass radius and concentrated mainly in the innermost regions.

In this work, we showed that major mergers in dwarf galaxies offer an explanation for the formation of peculiar systems such as And II and Phoenix, characterized by steep metallicity gradients and prolate rotation.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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