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How ram pressure induces U-type warps in simulated galactic discs

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Abstract. Warped stellar discs are often observed in edge-on galaxies. The most common type of warp is the S-type (or integral-shaped) warp, which is generally interpreted as the result of tidal interactions. Another kind of warp is the U-type (or bow-shaped) warp, in which both sides of the stellar disc are bent in the same direction. It has been proposed that jellyfish galaxies may develop U-type warps due to the drag force associated with ram pressure stripping. We aim to characterise the properties of warped stellar discs in ram pressure simulations. In particular, we wish to evaluate the role of the bulge in such galaxies. To this end, we carried out a set of hydrodynamical N-body simulations using a modified version of the Arepo code. To mimic the effects of ram pressure, we simulate a gas-rich disc galaxy within an idealise wind tunnel, where the surrounding gas has a given density and a given velocity. The galaxy receives the wind face-on. If the ram pressure is sufficiently strong, the stellar disc develops a subtle but measurable U-shaped warp within 100 Myr. In agreement with previous simulations, the stellar disc edges are bent towards the side opposite to the jellyfish tail. Additionally, we found that the bulge plays an anchoring role, in the sense that bulgeless galaxies are prone to experience more intense U-type warps.

Resumo. Discos estelares deformados são frequentemente observados em galáxias vistas de perfil. O tipo mais comum de deformação é a do tipo S (ou em forma de integral), que geralmente é interpretada como resultado de interações de maré. Outro tipo de deformação é a do tipo U (ou em forma de arco), na qual ambos os lados do disco estelar estão curvados na mesma direção. Foi proposto que galáxias do tipo jellyfish possam desenvolver deformações do tipo U devido à pressão de arraste associada à remoção de gás. Nosso objetivo é caracterizar as propriedades dos discos estelares deformados em simulações de pressão de arraste. Em particular, desejamos avaliar o papel do bojo nessas galáxias. Para isso, realizamos um conjunto de simulações hidrodinâmicas de N-corpos utilizando uma versão modificada do código Arepo. Para imitar os efeitos da pressão de arraste, simulamos uma galáxia com disco rico em gás em um túnel de vento idealizado, onde o gás ao redor possui uma densidade e uma velocidade definidas. A galáxia recebe o vento frontalmente. Se a pressão de arraste for suficientemente intensa, o disco estelar desenvolve uma deformação sutil, mas mensurável, em forma de U dentro de 100 Myr. Em concordância com simulações anteriores, as bordas do disco estelar se curvam para o lado oposto à cauda da galáxia jellyfish. Além disso, descobrimos que o bojo exerce um papel estabilizador, no sentido de que galáxias sem bojo são mais propensas a experimentar intensas deformações do tipo U.

Keywords. Galaxies: clusters: intracluster medium – Methods: numerical

1. Introduction

Warped stellar discs are frequently seen in galaxies viewed edge-on. The most common form is the S-type (or integral-shaped) warp, commonly understood as a consequence of tidal interactions. Another form, known as the U-type (or bow-shaped) warp, features both sides of the stellar disc curving in the same direction. U-warps are less frequent in observations and their origin is not fully understood (Ann & Park 2006; Zee et al. 2022). It has been suggested that U-type warps might develop in the context of ram pressure stripping (Smith, Fellhauer, & Assmann 2012). This phenomenon was also noticed in the simulations of Lee et al. (2022).

Here we aim to explore the development of U-warps in simulated galaxies. Specifically, we wish to evaluate the role played by the presence of the bulge in this phenomenon.

2. Simulation setup

In order to explore the phenomenon of ram pressure stripping, we created a wind tunnel setup. The box has dimensions of $100 \times 100 \times 200$ kpc, containing a gas with uniform density ($\rho = 10^{-26}\,\mathrm{g\,cm^{-3}}$) and temperature ($kT = 2\,\mathrm{keV}$). This gas is meant to represent a portion of the intracluster medium (ICM). The ICM gas is set with a velocity of $v_z = 1000\,\mathrm{km\,s^{-1}}$.

Additionally, we created initial conditions for a galaxy consisting of a stellar disc, a gas disc and a dark matter halo. Optionally, the bulge is included. The galaxy with bulge is labelled ‘B’. The galaxy with no bulge is labelled ‘NB’. The masses of the stellar disc, gas disc and bulge (when present) are, respectively 5, 2 and $2 \times 10^{10}\,\mathrm{M_\odot}$. Each galaxy is relaxed in isolation for 1 Gyr.

The galaxy is then placed at rest in the centre of the rectangular box, where it is subjected to a face-on wind for a period of 0.2 Gyr. Simulations are carried out with the moving-mesh code Arepo (Springel 2010; Weinberger, Springel, & Pakmor 2020), including star formation.

3. Results

Fig. 1 displays edge-on projections of the stellar component of both galaxies, seen at the end of the simulation ($t = 0.2$ Gyr). Visual inspection already indicates that the discs are not symmetric with respect to the $z = 0$ plane. In Fig. 1, the wind flows from top to bottom. This means that the jellyfish gas tail (not shown) extends towards the negative side, i.e. $z < 0$. Thus we notice that the edges of the stellar discs are bent forward with respect to the centre of density. In this visualization, the stellar component is separated into old stars and young stars. This highlights that the U-warp is present to some degree in both populations. The comparison between the B and NB models suggests

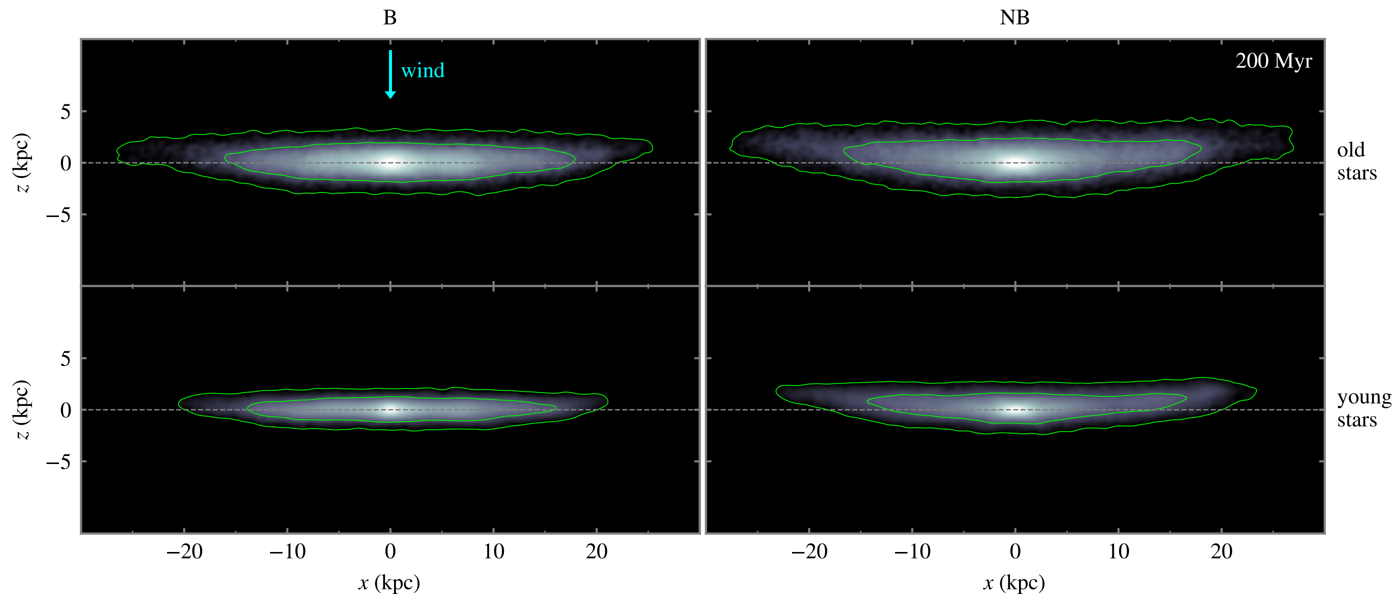

Figure 1. Old (top) and young (bottom) stellar populations seen edge-on at the end of the simulation (t = 0.2 Gyr), comparing models with (left) and without bulge (right).

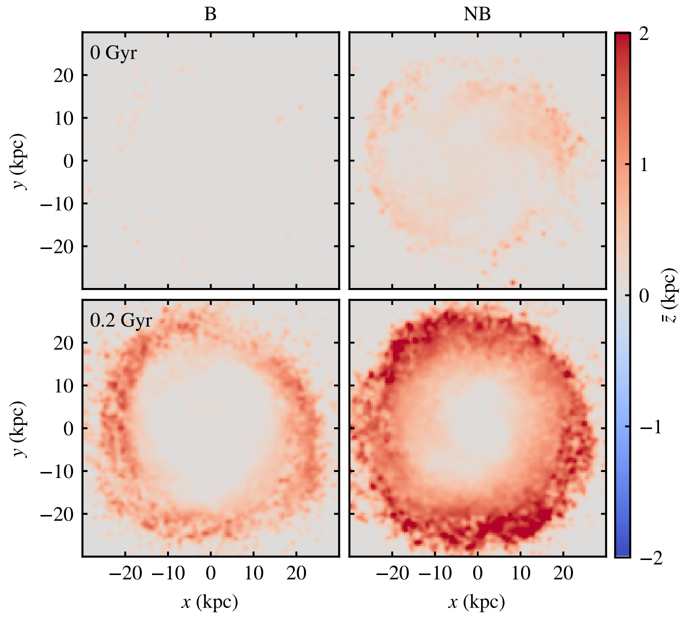

Figure 2. Maps of mean stellar height at t = 0 Gyr (top) and at t = 0.2 Gyr (bottom), comparing models with (left) and without bulge (right).

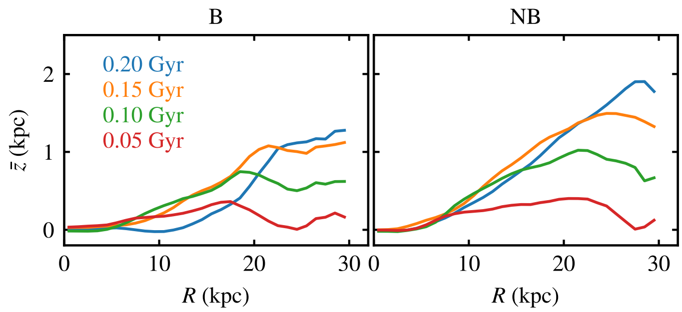

Figure 3. Radial profiles of mean stellar height at different times, comparing models with (left) and without bulge (right).

by eye that the effect is marginally more pronounced in the NB case. This will be quantified in greater detail in the subsequent figures.

Face-on views are presented in Fig. 2, which shows the mean stellar density, taking all stars into account. At t = 0 Gyr (upper panels of Fig. 2), the NB galaxy exhibits some minor intrinsic warping, even before having been subjected to ram pressure inside the wind tunnel. This reveals that the bulgeless galaxy must be intrinsically more prone to such instability. At t = 0.2 Gyr (bottom panels of Fig. 2), it is clear that the NB galaxy is more intensely warped than the B galaxy.

In order to examine how this phenomenon developed over time, we show in Fig. 3 the radial profiles of mean height at a few selected times. Soon after the initial times, the NB galaxy develops more intense warping than the B galaxy. By the end of the simulations (t = 0.2 Gyr; blue lines in Fig. 3), the most intense warps are present at the outermost radii of both galaxies. At earlier times, however, the peak warps were found at intermediate radii.

Such evolution is radius is confirmed by the more detailed analysis in Fig. 4, which shows the mean stellar heights for all times and all radii. In both panels, the general upwards pattern indicates that the U-warp must be moving inside-out. Again, the phenomenon is clearly more intense in the NB case. IN the B galaxy, a relevant warp is also noticeable at the disc outskirts at earlier times.

Finally, we wish to provide some way of quantifying this phenomenon which is more connected to observational measurements. The mean heights analysed so far require knowledge of the z coordinates of the simulated stellar particles. In observations, U-warps can only be adequately identified in edge-on galaxies. A direct geometric measurement of the warp amplitude would be an angle α defined as such: the angle between the z plane and the line connecting the centre of the galaxy to the edge of the warp. An average may be taken considering both right and left sides.

With this straightforward angle measurement, we can interpret Fig. 5 as an evolution of the warp amplitude. The final amplitudes of almost 3° (for B) and almost 4° (for NB) are consistent with the ranges measured in the observational sample of Zee et al. (2022).

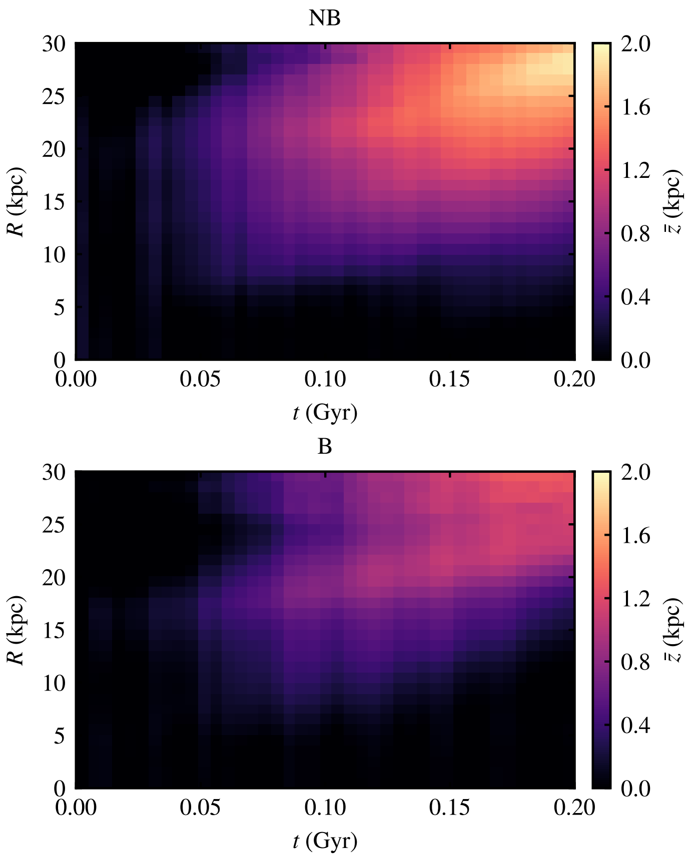

Figure 4. Mean stellar heights (colors) shown for all times and all radii, comparing models with (top) and without bulge (bottom).

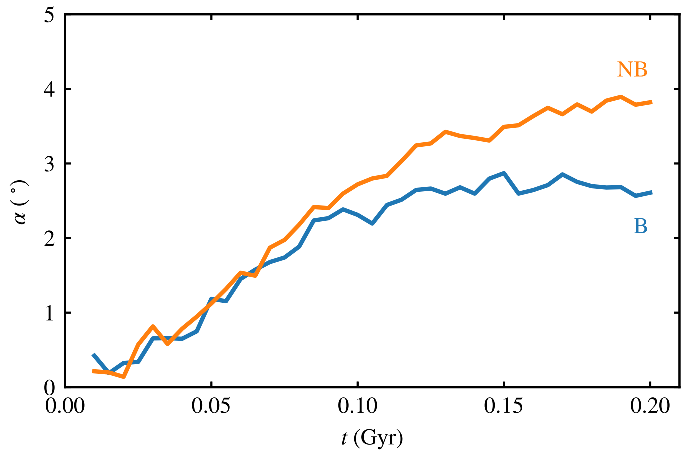

Figure 5. Evolution of the amplitude of the warp, comparing models with (blue) and without bulge (orange).

4. Conclusions

We carried out idealised wind tunnel simulations of galaxies undergoing ram pressure stripping. We found that stellar U-warps develop spontaneously in such ram pressure simulations, with the stellar disc bent in the direction opposite to the gas tail. This is consistent with previous findings (Smith, Fellhauer, & Assmann 2012; Lee et al. 2022). Additionally, our preliminary results suggest that the bulge plays an anchoring role, preventing stronger warping.

More systematic sets of simulations are needed to address the general question of what the conditions are for a U-warp to develop. An exploration of the parameter space (of both ICM properties and galactic properties) might reveal whether environmental dependence is to be expected and how it relates to observations of U-warps. Furthermore, the output of such wind tunnel simulations may help shed some light on the reasons why observed U-warps tend to be bluer than S-warps (Lee et al. 2022). Finally, investigating warped galaxies found in the IllustrisTNG simulations (Yun et al. 2019) would bring more insight into the realistic history of such galaxies.

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