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Warps induced by satellites on barred and non-barred galaxies

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Abstract. Minor mergers can distort the edges of the galactic disk, inducing vertical asymmetries, such as warps. They can also impact the development of a galactic bar. In this study, we aim to compare barred and non-barred galaxy models and their susceptibility to warping. We use Gadget-4 simulations of a barred and a non-barred galaxies interacting with satellites of different masses ($0.1 \times 10^{10}\mathrm{M}_\odot$, $0.5 \times 10^{10}\mathrm{M}_\odot$ and $1 \times 10^{10}\mathrm{M}_\odot$) and initial orbital distances (10, 20 and 30 kpc). In the barred galaxy, we measured the bar strength, and found that the masses of the satellites determine the level of destruction of the bar. The time in which the bar will be weakened or destroyed depends on the initial orbital radius of the perturber. In both models, we measured the intensity of the bending mode to describe the warp. Our analysis indicated that the induced warps are stronger in the barred galaxy compared with the non-barred galaxy, even if they are perturbed by the same satellites.

Resumo. Interações e fusões podem distorcer as bordas do disco galáctico, induzindo assimetrias verticais, como warps. Elas também podem impactar o desenvolvimento da barra. Neste estudo, nosso objetivo foi comparar modelos de galáxias barradas e não barradas e sua susceptibilidade a formação de warps. Nós usamos simulações feitas com o código Gadget-4 de galáxias barradas e não barradas interagindo com satélites de diferentes massas ($0.1 \times 10^{10}\mathrm{M}_\odot$, $0.5 \times 10^{10}\mathrm{M}_\odot$ e $1 \times 10^{10}\mathrm{M}_\odot$) e raios orbitais iniciais (10, 20 e 30 kpc). Na galáxia barrada, medimos a força da barra, e constatamos que a massa dos satélites determina o nível de destruição da barra. O momento no qual a barra será enfraquecida ou destruída depende do raio orbital inicial do perturbador. Em ambos os modelos, nós medimos a intensidade do modo de torção para descrever o warp. Nossas análises indicaram que warps induzidas são sempre mais intensas na galáxia barrada em comparação com a não barrada, ainda que sejam perturbados pelo mesmo satélite.

Keywords. Galaxies: interactions – Galaxies: kinematics and dynamics – Galaxies: structure

1. Introduction

The interactions with satellites can distort the edges of a galactic disk, inducing vertical asymmetries, such as S-shaped warps. They can also impact the development of a galactic bar. In this study, we aim to compare barred and non-barred galaxy models and their susceptibility to develop warps induced by satellites.

2. Methods

We set two models of galaxies using the `galstep` code (Ruggiero & Lima Neto (2017)) to create the initial conditions and the `Gadget-4` code (Springel et al (2021)) to run the simulations.

Our first central galaxy model has a strong bar (model B). It is composed of a stellar disk ($M_\mathrm{d} = 4 \times 10^{10}\mathrm{M}_\odot$), a bulge ($M_\mathrm{b} = 1 \times 10^{10}\mathrm{M}_\odot$) and a dark matter halo ($M_\mathrm{h} = 1 \times 10^{12}\mathrm{M}_\odot$). The second model has a weak bar, but because of the contrast with the much stronger bar in model B, we labelled it non-barred (model NB). This model has the same mass as model B, but the disk is initially composed entirely of gas, and includes cooling and star formation. The final morphology of the galaxies, at t = 14 Gyr is shown in Fig. 1.

In model B, we used the $m = 2$ Fourier mode of the projected mass distribution to measure the bar strength (e.g.Athanassoula et al (2013); Cuomo et al (2019)). A_2 is given by equation 1:

$$A_2 = \max\left(\frac{\sqrt{a_2^2 + b_2^2}}{a_0}\right), \tag{1}$$

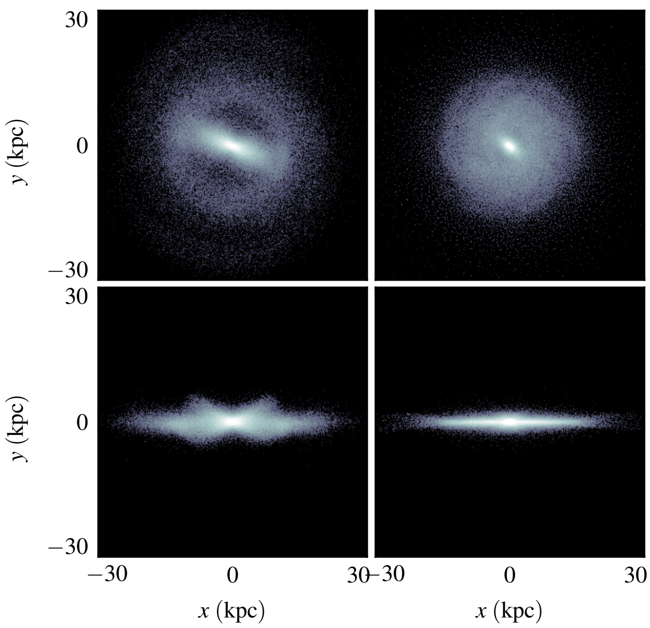

Figure 1. Morphology of the galaxies B and NB at the end of the simulation (14 Gyr).

where a_m and b_m are shown by equations 2 and 3:

$$a_m(R) = \sum_{i=0}^{N_R} m_i \cos(m\,\theta_i),\ m = 0, 1, 2... \tag{2}$$

$$b_m(R) = \sum_{i=0}^{N_R} m_i \sin(m\,\theta_i),\ m = 1, 2... \qquad (3)$$

with m_i being the mass in each ring i of radius R.

In addition to simulations of isolated galaxies, we ran these same models interacting with satellites of different masses (M1 $= 0.1\times10^{10}$M$_\odot$, M2 $= 0.5\times10^{10}$M$_\odot$, M3 $= 1\times10^{10}$M$_\odot$) and initial orbital distances (R1 = 10 kpc, R2 = 20 kpc, R3 = 30 kpc). The satellites were introduced at $t = 8$ Gyr, in polar orbits.

For the analysis of vertical asymmetries, we measured the intensity of the bending mode A_1, using the $m = 1$ Fourier mode, as shown by equation 4:

$$A_1 = \sqrt{a_1^2 + b_1^2}. \qquad (4)$$

where a_m and b_m are given by equations (5) and (6):

$$a_m(R) = \frac{1}{N_R}\sum_{i=0}^{N_R} z_i \cos(m\,\theta_i),\ m = 0, 1, 2... \qquad (5)$$

$$b_m(R) = \frac{1}{N_R}\sum_{i=0}^{N_R} z_i \sin(m\,\theta_i),\ m = 1, 2... \qquad (6)$$

where z_i is the height in each ring i of radius R and N_R is the number of particles in each ring.

3. Results

The close passage of the satellites caused changes in the strength of the bar in model B, as shown in Fig 2.

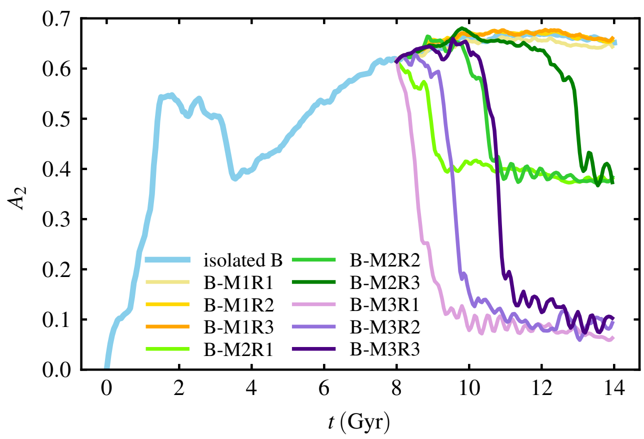

Figure 2. Evolution of bar strength in isolated and perturbed models of the barred galaxy.

The interaction with the satellites also induced warps in both models. In the maps of A_1, the lighter colors mark the areas where the warp is most intense, as shown in Figs. 3 and 4. In Fig. 5, there is an example of the final morphology of models B-M3R1 and NB-M3R1, showing the distortions at the edges.

4. Conclusions

We observed that after the interaction, in model B, the bar can be preserved, weakened or destroyed. The level of bar weakening is determined by the mass of the satellite. And the time it takes depends on the initial orbital radius. The analysis of vertical asymmetries indicated that that satellites induce warps in the B and NB models, and that the intensity of the distortion depends mainly on the mass of the perturber. In addition, warps are stronger in the barred galaxies in comparison with the non-barred galaxies, even if they are perturbed by the same satellites.

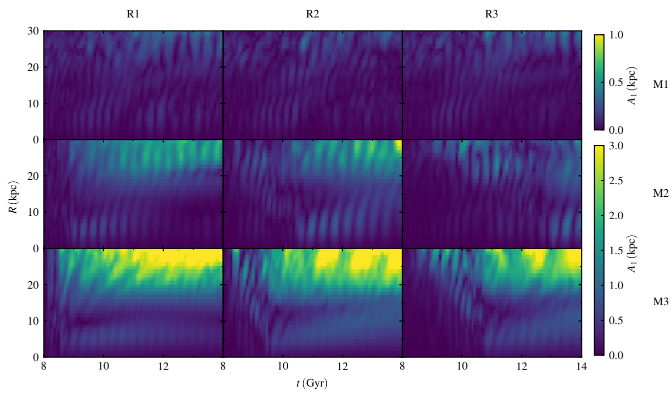

Figure 3. A_1 for all perturbed models of the B galaxy at $t = 14$ Gyr.

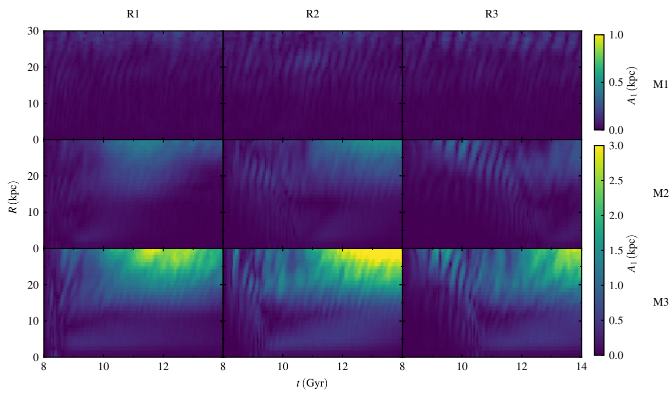

Figure 4. A_1 for all perturbed models of the NB galaxy at $t = 14$ Gyr.

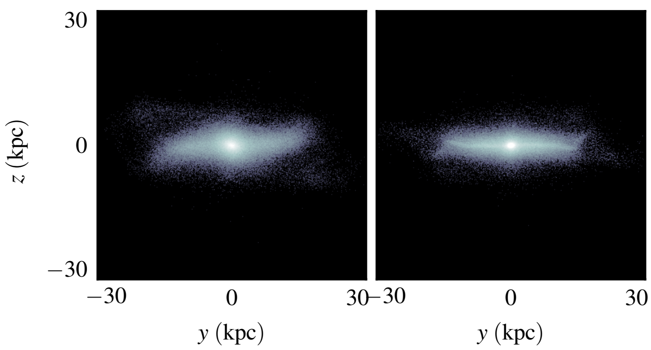

Figure 5. Warps induced in B-M3R1 and NB-M3R1 models.

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