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Warped disks in simulated barred galaxies

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Abstract. The close passage of dwarf galaxies can induce vertical asymmetries in the disk of the host galaxy. We aim to analyze the effects of warps induced by satellites on barred and non-barred galaxies, their evolution and amplitudes. In this study, we use *N*-body simulations of galaxies interacting with satellites of varying 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). We found that the vertical asymmetry will always be stronger in the barred galaxy, regardless of the mass or orbit of the perturber.

Resumo. A passagem próxima de galáxias anãs pode induzir assimetrias verticais no disco de galáxias. Nosso objetivo foi analisar os efeitos de warps induzidas por satélites em galáxias barradas e não barradas, sua evolução e amplitudes. Neste estudo, usamos simulações de *N*-corpos de galáxias 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 distâncias orbitais iniciais (10, 20 e 30 kpc). Constatamos que a assimetria vertical sempre será mais forte na galáxia barrada, independente da massa do perturbador.

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

1. Introduction

Bars are elongated structures in the center of spiral galaxies. Another feature that can appear on galactic disks are S-shaped warps, vertical asymmetries in which the disk has one side bent upwards and the other downwards. Possible explanations for this morphology include close passages the interaction with a satellite galaxy (e.g. Semczuk et al (2020)), that can also perturb the bar. In this study, we investigate the influence of the mass and the orbital radius of a satellite on the bar strength and on vertical asymmetries of the host galaxy: compared to a non-barred galaxy, is a barred galaxy more resilent against warping, or more succeptible to it?

2. Methods

We used 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.

We first aimed to establish two models of galaxies: one strongly barred and one without bar. Since bars appear spontaneously in a large number of studies with N-body simulations (Athanassoula & Misiriotis (2002)), we tried varying different parameters in order to obtain a non-barred galaxy. We found that adding a high fraction of gas (75%) to the disk suppressed bar formation.

With the two models well established, we also ran simulations with the addition, at $t = 8$ Gyr, of satellites of different masses ($0.1\times10^{10}\mathrm{M}_{\odot}$, $0.5\times10^{10}\mathrm{M}_{\odot}$ and $1\times10^{10}\mathrm{M}_{\odot}$) and initial orbital radii (10, 20 and 30 kpc). The orbit chosen was a polar orbit in all cases.

In order to measure the bar strength (A_2), we used the coefficients of the Fourier series, quite sensitive to non-axisymmetric configurations. A_2 is given by equation 1:

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

where a_n and b_n are shown by equations 2 and 3:

$$a_n(R) = \sum_{i=0}^{N_R} m_i \cos(n\,\theta),\; n = 0, 1, 2... \tag{2}$$

$$b_n(R) = \sum_{i=0}^{N_R} m_i \,\mathrm{sen}(n\,\theta),\; n = 1, 2... \tag{3}$$

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

Fig. 1 shows A_2 and for barred and non-barred galaxies and the final disk configuration in each case.

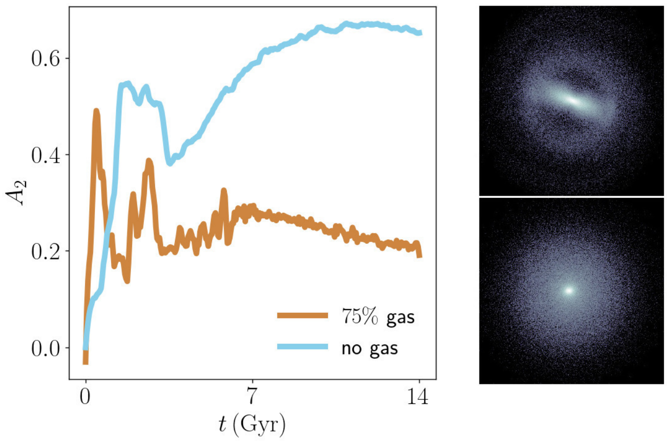

Figure 1. Left: evolution of bar strength. Right: appearance of the galaxies at 14 Gyr.

For the analysis of vertical asymmetries, we examined maps of the mean height z. Also, considering z in the outermost ring of the galactic disk (20 kpc < r < 30 kpc), we calculated the mean of the highest point (peak) and the lowest point (valley) to find the maximum amplitude of the warp ($A_{\max}$).

3. Results

Fig. 2 shows the evolution of the bar strength after the satellites have been added. In the left panel, we have A_2 for the barred galaxy. It is possible to observe the influence of the satellite's mass in how much the bar will lose strength, and the satellite's orbital radius in the moment where this change will occur. In the right panel, we have A_2 for the non-barred galaxy. Regardless of the perturber's mass or initial orbital radius, the final situation does not change significantly, because this galaxy never developed a strong bar.

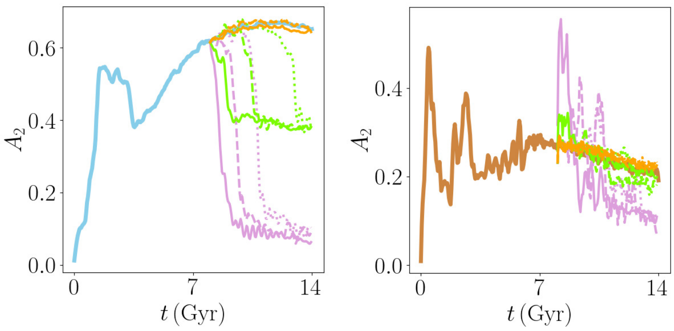

FIGURE 2. Evolution of the bar strength with the inclusion of the satellites. The colors of the lines (orange, green and lilac) represent A_2 of the least massive, intermediate and most massive satellites, respectively. The solid line represents A_2 of the orbital radius of 10 kpc, the dashed line is the 20 kpc radius and the dotted line is the 30 kpc radius.

Figs. 2 and 3 show the induced warp morphology.

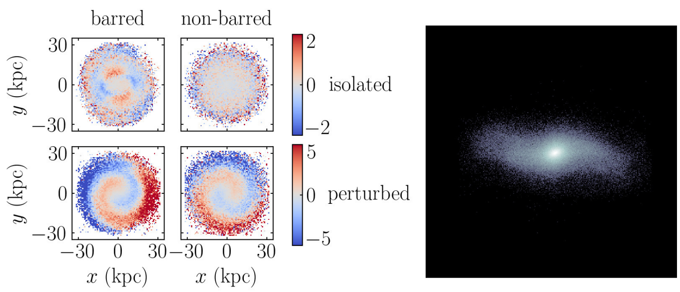

FIGURE 3. Left: Maps of z for the cases of barred and non-barred galaxy, isolated and interacting with a satellite of mass $1 \times 10^{10} M_\odot$ and orbital radius 30 kpc, at $t = 14$ Gyr. Note the different ranges in the colorbar. Right: S-shaped warp induced in the barred galaxy by this satellite.

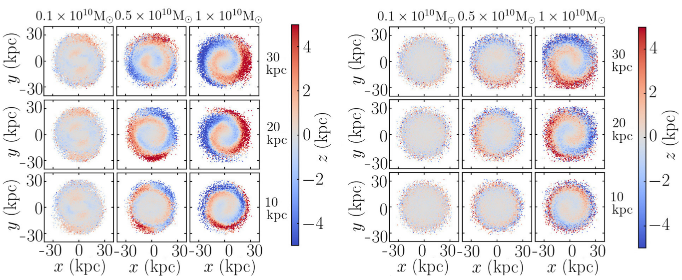

FIGURE 4. Left: maps of z for the barred perturbed galaxy. Right: maps of z for the non-barred perturbed galaxy.

Fig. 5 show the difference of A_{max} for the barred and the non-barred galactic disks.

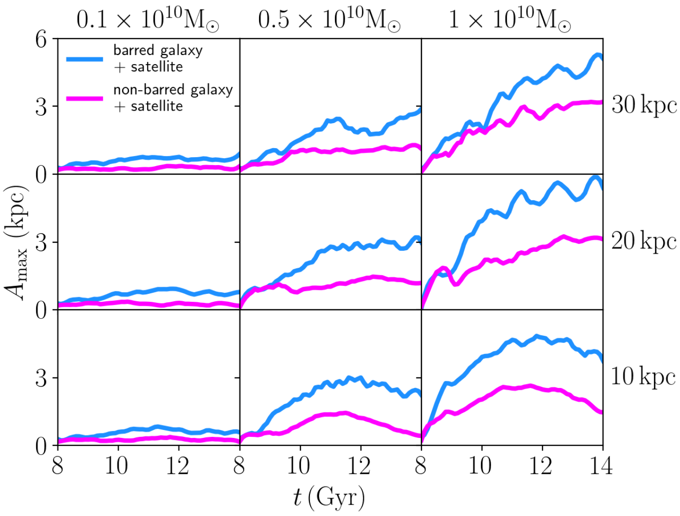

FIGURE 5. Maximum amplitude of the warp.

It is clear that the mass of the perturber has a direct influence on the maximum amplitude of the warp. The initial orbital radius, however, doesn't seem to contribute significantly.

In all cases, A_{max} is bigger for the barred galaxy.

4. Conclusions

Minors mergers events can be a reason for considerable bar weakening (e.g. Ghosh et al (2021)). In this study, we found that the mass of the pertuber determines the fate of the bar:

- If the mass of the perturber is small ($0.1 \times 10^{10} M_\odot$), the bar survives.
- With an intermediate-mass perturber ($0.5 \times 10^{10} M_\odot$), the bar is weakened.
- The interaction between the galaxy and the most massive satellite ($1 \times 10^{10} M_\odot$) caused the destruction the bar.

Furthermore, the orbital radius of the perturber determines the time of bar destruction or weakening: satellites in closer orbits destroy or weaken the bar before satellites in more distant orbits.

The mass of the satellite also determines the maximum amplitude of the warp, and it seems to be more relevant than orbital radius.

Finally, comparing the barred and the non-barred galaxies and their susceptibility to induced asymmetries, we found that the warp will always be stronger in the barred galaxy, regardless of the mass or orbit of the satellite.

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