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# Dark matter halo evolution in $N$-body simulations of barred galaxies

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**Abstract.** Barred galaxies are a very common type of galaxy and their features are of special interest in the study of dark matter. This work aims to investigate the relationship between the stellar disk and the dark matter halo, focusing on its consequences on the formation of the halo bar. Using $N$-body simulations, we analyse properties of the halo bar such as length, strength, shape, transfer of angular momentum and orientation, in order to correlate them with the properties of the disk bar. We find that the orientations of the bars remain the same during the entire simulation. The inner dark matter halo is initially spherical and becomes elongated as the stellar bar forms. The halo bar is shorter and weaker than the disk bar, though both grow simultaneously and the buckling of the disk is mimicked by the halo bar. The galaxy with the weaker stellar disk bar also displays a weaker inner halo bar. The angular momentum transfer from the stellar disk to the inner halo is lower than expected for its mass. Preliminary results indicate that this phenomenom is related to the formation of the halo bar and the strength of the stellar bar may be the governing factor driving the formation and evolution of the halo bar.

**Resumo.** Galáxias barradas são um tipo muito comum de galáxia e suas características são de especial interesse no estudo da matéria escura. Este trabalho tem como objetivo investigar a relação entre o disco estelar e o halo de matéria escura, focando em suas consequências na formação da barra do halo. Analisamos, através de simulações de $N$-corpos, propriedades da barra do halo como comprimento, força, forma, transferência de momento angular e orientação, a fim de correlacioná-los com as propriedades da barra do disco. Constatamos que as orientações das barras permanecem as mesmas durante a simulação. O halo de matéria escura interior é inicialmente esférico e torna-se alongado enquanto a barra estelar se forma. A barra do halo é mais curta e mais fraca do que a barra do disco, embora ambas cresçam simultaneamente e a diminuição momentânea na força da barra devida ao *buckling* do disco seja reproduzida pela barra do halo. A galáxia com a barra do disco estelar mais fraca exibe a mesma característica na barra interior do halo. A transferência de momento angular do disco estelar para o halo interior é menor do que o esperado para a sua massa. Resultados preliminares indicam que este fenômeno está relacionado à formação da barra do halo e a força da barra estelar pode ser o fator principal na formação e evolução da barra do halo.

**Keywords.** Galaxies: evolution – Galaxies: kinematics and dynamics – Galaxies: halos – Dark matter – Methods: numerical

## 1. Introduction

Barred galaxies are stellar structures with a bar-shaped inner region, known to make up to one or two-thirds of all spiral galaxies (e.g. Masters, et al. 2011). These bars are formed under the total gravitational potential of the galaxy, therefore the shape and dynamics of these objects are highly influenced by the presence of dark matter. Also, it has been shown that the transfer of angular momentum from the disk to the dark matter halo plays an important role in the formation of the stellar bar (Athanassoula & Misiriotis 2002), and an intriguing detail in the simulations is the formation of an elongated structure in the mass distribution of dark matter. This structure is analogous to the disk bar and has been named *dark matter bar* (Colín, Valenzuela & Klypin 2006), *halo bar* (Athanassoula 2005), *ghost bar* (Berentzen & Shlosman 2006) and *shadow bar* (Petersen, Weinberg & Katz 2016). Recently, Collier, Shlosman & Heller (2018) analysed the effect of spinning halos on the dark matter bars. The development of a halo bar points out to the fact that the dark matter halo itself is affected by the presence of a stellar bar, and this provides interesting results. This work aims to analyse the mutual interactions between the disk bar and the halo bar by characterizing their properties and evolution.

## 2. Methods

We use some of the $N$-body hydrodynamic simulations from Athanassoula, Machado & Rodionov (2013), in order to analyse a set of galaxies with different initial conditions carried out with a version of the code `Gadget-2` (Springel 2005) that includes star formation. Those simulations consist of $10^6$ dark matter particles and different initial gas fractions. We compare the development of a strongly barred galaxy and a weakly barred one through a period of 10 Gyr. The strongly barred one is composed by $2 \times 10^5$ disk particles whereas the weakly barred one comprises half of that and, additionally, $5 \times 10^5$ gas particles, which form new stars as the simulation carries on. For further details, see Athanassoula, Machado & Rodionov (2013).

In order to measure the bar strength, we used the relative amplitude of the $m = 2$ mode of the Fourier decomposition of the mass distribution. The maximum value of this amplitude, as a function of radius, is the bar strenght $A_2$. Their axial ratios were obtained through the diagonalization of the inertia tensor, calculated inside non-spherical isodensity shells with a constant number of particles. Bar lengths were defined as the radius at which the $m$=2 amplitude has dropped to half its maximum value. The orientation of the bars was obtained via the Fourier analysis. We measured the transfer of angular momentum to the dark matter halo considering two distinc regions: the inner halo (comprising the inner 5 kpc), and the outer halo, making up the rest.

## 3. Results

We found negligible differences between the bar orientations along the entire simulations. The dark matter halo bar is shorter in length than the stellar disk bar. The disk bar is much stronger than the halo bar, but their evolutions are very similar (Fig. 1). The galaxy with gas particles indeed develops weaker bars.

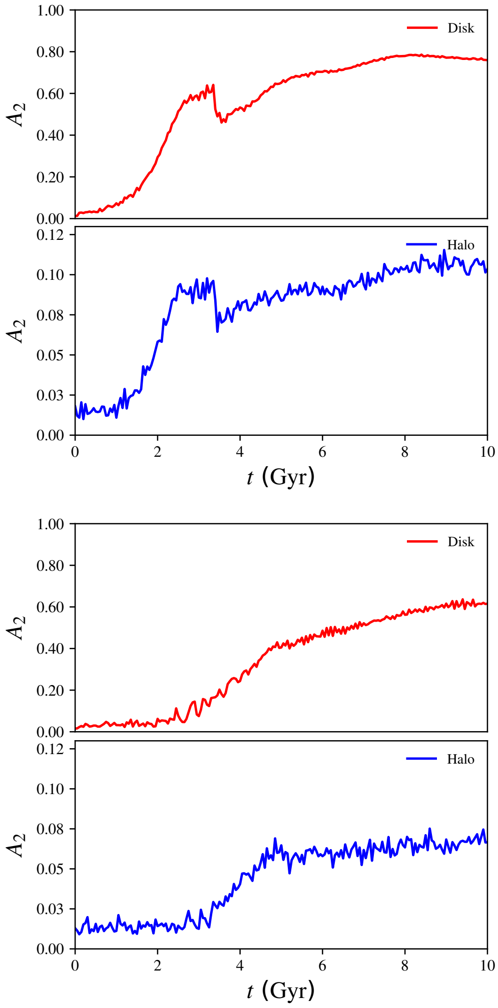


**Figure 1.** Bar strengths of the stellar bar and of the halo bar as a function of time. Notice the different scales: the halo bars are much weaker. (a) Strong bar galaxy; (b) Weak bar galaxy.

Around $t$ = 3.5 Gyr, the strongly barred simulated galaxy undergoes a slight bending, known as buckling (Martinez-Valpuesta & Shlosman 2004), which temporarily reduces the strength of the disk bar. We found that the decrease in strength is mimicked by the dark matter halo bar. The dark matter halos remain quite spherical at large radii. In the inner region, the dark matter distribution becomes elongated, with axis ratios of approximately $b/a = 0.7$ and $c/a = 0.7$ for the strongly barred galaxy, and $b/a = 0.8$ and $c/a = 0.8$ for the weakly barred galaxy. The dark matter halo absorbs angular momentum from the disc. However, the inner part of the halo gains much less than the outer, even when normalized by mass (Fig. 2). In the strong bar case, the transfer of angular momentum is much larger, as one would expect. In both cases, the inner halo contributes proportionally less to the absorption of angular momentum. In the strong bar case, the relative contribution of the inner halo is even smaller. This indicates that the disk bar, after being formed, drives the growth of the dark matter halo bar. Further investigation of the resonant orbits may reveal more details about the mutual interaction between the two bars.

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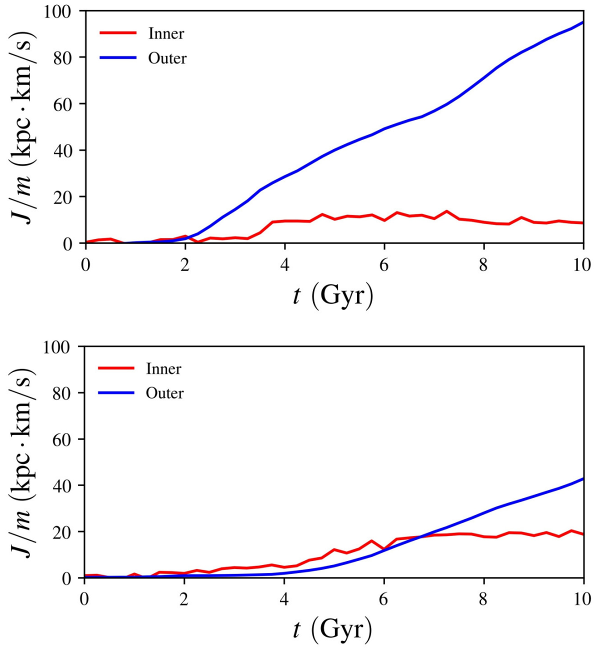


**Figure 2.** Specific angular momentum of the halo as a function of time. (a) Strong bar galaxy; (b) Weak bar galaxy.

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