BAR-HALO INTERACTION AND BAR GROWTH
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ABSTRACT

I show that strong bars can grow in galactic disks, even when the latter are immersed in halos whose mass within the disk radius is comparable to, or larger than, the mass of the disk. I argue that this is due to the response of the halo and in particular to the destabilizing influence of the halo resonant stars. Via this instability mechanism, the halo can stimulate, rather than restrain, the growth of the bar.

Subject headings: galaxies: evolution — galaxies: halos — galaxies: kinematics and dynamics

1. INTRODUCTION

Galactic disks are generally unstable and form bars within a few dynamical timescales (see, e.g., Athanassoula 1984 or Sellwood & Wilkinson 1993 for reviews). The first remedy proposed against this instability is to immerse the disk in a massive halo component. Ostriker & Peebles (1973), from an insightful analysis of N-body simulations with a very small number of particles, were the first to outline the stabilizing influence of halos. They further suggested that halo-to-disk mass ratios of 1–2.5 (interior to the disk) are required for stability. Athanassoula & Sellwood (1986) measured the growth rates of the most unstable bar-forming modes in two-dimensional N-body simulations and showed that the growth rate is smaller in cases with large halo-to-disk mass ratios. Unfortunately, no such analysis has been made for fully self-consistent three-dimensional N-body simulations. On the other hand, Athanassoula & Misiriotis (2002, hereafter AM) and Athanassoula (2002a, 2002b) argue that stronger bars can grow in simulations with initially very high halo-to-disk mass ratios than in simulations with lower halo-to-disk mass ratios. In order to understand whether the above pieces of evidence are contradictory, and, if so, to attain a coherent picture, I will examine in this Letter the role of the halo in the formation of the bar. Several papers have focused on the influence of the halo on the slowing down of the bar (e.g., Tremaine & Weinberg 1984; Weinberg 1985; Combes et al. 1990; Little & Carlberg 1991; Hernquist & Weinberg 1992; Athanassoula 1996; Debattista & Sellwood 1998, 2000). This Letter is complementary, since it concentrates on the role of the halo in determining the bar growth. The discussion will focus on three simulations. The results, however, are based on a much larger set of simulations, leading to the same conclusions.

2. RESULTS ON BAR FORMATION

I will describe the results of three fully self-consistent three-dimensional N-body simulations of isolated galaxies consisting of a disk and a halo component. The initial conditions and the numerical methods are described in AM, whose notation I follow here. The three initial conditions have exponential disks of unit mass and scale length, scale height $z_0 = 0.2$ and $Q = 1$. Their halos are 5 times as massive as their disks and have different degrees of central concentration. They are initially isotropic, spherical, and nonrotating, with a radial density profile

$$\rho_p(r) = \frac{M_h}{2\pi^{3/2} r_c^3} \frac{\alpha \exp(-r^2/r_c^2)}{r^2 + \gamma^2},$$

with $M_h = 5$ and $r_c = 10$. The parameter $\alpha$ is a normalization constant defined by

$$\alpha = \left\{1 - \sqrt{\pi} q \exp(q^2)[1 - \text{erf}(q)]\right\}^{-1},$$

where $q = \gamma/r_c$ and erf is the error function (Hernquist 1993). The initial circular velocity curves of the three models are shown in the upper panels of Figure 1. The first simulation, hereafter model MD, has $\gamma = 5$, and its disk dominates in the inner parts, roughly up to $r = 5$. In the other two (hereafter models MH and RH, respectively), $\gamma = 0.5$, and the halo contribution is slightly larger than that of the disk up to the maximum of the disk rotation curve and considerably so at larger radii. Model RH is identical to model MH, except that its halo is rigid—i.e., given by a potential imposed on the disk particles—and does not evolve during the simulation. The number of particles in the simulations is 1,131,206, 1,163,030, and 200,000, respectively. The simulations were run on a GRAPE-5 system with a softening of 0.0625 and a time step of 0.015625. I assessed the numerical robustness of my results by trying double the number of particles, different scalings of the initial circular velocity curves of the three models are striking. A comparison of models MD and MH shows that the bar that grew in the initially more halo-dominated environment is stronger than the bar that grew in the disk-dominated environment. It is longer, and its iso-photographs are more rectangular-like. The strength of the bar can
be measured with the help of the relative amplitude of the Fourier components of the density or mass (AM), and the last row of panels in Figure 1 shows that indeed the MH bar is considerably stronger than the MD one. The $m = 4, 6,$ and 8 Fourier components of the face-on density of model MH are also considerably stronger than those of model MD (AM).

Very strong differences are also found when comparing models MH and RH. Model MH has a very strong bar, while model RH has a very mild oval in the innermost parts. Their edge-on views are also very different (not shown here; cf. Athanassoula 2002b for another example). Model MH seen side-on has a strong peanut, or X-shape, and a big bulgelike protuberance if seen end-on. Model RH shows no such features. Finally, the difference between their integrated Fourier components is striking.

The three models differ also in the way their bars evolve. In model MD, the bar grows very rapidly during the first part of the evolution, but little, if at all, after that. On the contrary, the growth of the bar in model MH during the first part of the evolution is slower than in MD but stays considerable, although less important than in the first part, till the end of the simulation. The pattern speed of model MH starts off higher than that of model MD but ends smaller. The pattern speed of MD also decreases with time, but less so (Debattista & Sellwood 1998, 2000). The pattern speed of the nonaxisymmetric component in RH cannot be measured reliably before $t = 300$ and after that does not show any signs of decrease. For models MD and MH, there is exchange of energy and angular momentum between the disk and halo components, so that the halo, which was initially nonrotating, displays rotation after the bar has grown. This is small for model MD and considerable for model MH, for which at $t = 900$ the halo has somewhat less than half of the angular momentum of the disk, i.e., not far from a third of the total.
3. THE ROLE OF THE HALO

In order to understand the role of the halo in the formation and evolution of the bar, I froze the potential at four selected times during each simulation and chose randomly 100,000 disk and 100,000 halo particles. I followed their orbits during 40 bar rotation periods and calculated their basic frequencies, namely, the angular frequency $\Omega$, the epicyclic frequency $\kappa$, and the vertical frequency $\kappa_z$. For the two latter ones, I used a spectral analysis technique (Binney & Spergel 1982; Laskar 1990). In most cases, there were several secondary peaks, and the frequency was determined by the main one. The angular frequency proved more difficult to calculate reliably, so I supplemented the spectral analysis with other, more straightforward methods, based on following the angle as a function of time. Agreement between the values for the angular frequency obtained by the various methods was found to be satisfactory for 85% or more of the particles.

An orbit is resonant if there are three integers $l$, $m$, and $n$ such that $l n \Omega + m \kappa + n \kappa_z = n \Omega_z$, where $\Omega_z$ is the pattern speed of the bar. I will here restrict myself to radial (planar) resonances, for which $n = 0$. The most important such resonances are the inner Lindblad resonance (ILR), where $l = -1$ and $m = 2$, corotation resonance (CR), where $l = 0$, and the outer Lindblad resonance (OLR), where $l = 1$ and $m = 2$. At CR, the particles have the same angular frequency as the bar, while at the other resonances they make $m$ radial oscillations in the time they make $l$ revolutions around the center of the galaxy. Figure 2 shows the number of particles (orbits), $N_R$, that have a frequency ratio $R = (\Omega - \Omega_z)/\kappa$ within a bin of a given width centered on a value of this ratio, plotted as a function of $R$.

Let me first describe the results for the disk components of MD and MH. The distribution in both cases is far from homogeneous, with strong peaks at the location of the main resonances. The highest peak, both for the MH and the MD disk, is for $(\Omega - \Omega_z)/\kappa = 0.5$, i.e., at the ILR. Indeed, orbits making two radial oscillations in the time they make one revolution around the center of the galaxy are the backbone of the bar. In principle, $x_4$-type orbits (see Contopoulos & Grosbøl 1989 for a review) could also be found in this peak. I have, however, verified that the vast majority of the orbits here are $x_1$-type.

The ILR peak in the MH case is roughly 1.5 times higher than in MD, consistent with the fact that the bar in the MH case is stronger. Model MD has a sizeable CR peak and a much lower one at the OLR, while model MH has only a small CR peak and no OLR one. The ratio of the height of the CR peak to that of the ILR peak is roughly 0.6 for the MD case, while for model MH it is only 0.09. These differences are, to a large extent, due to the difference in the corotation radii of the two models. Thus, at time 800 the CR radius is 7.1 for model MH and 4.6 for model MD. Similar differences are found for the OLR radii of the two models. Therefore, these two resonances are in the outer parts of the MH disk and can trap only few particles. This is not the case for model MD, and the differences in the trappings are reflected in the differences in the heights of the respective resonant peaks. Model MH has also a clear peak at the inner $1:6$ resonance and perhaps one at the $1:4$ resonance. Model MD has a clear inner $1:4$ peak.

The big surprise, however, comes from the halo component. So far considered as non-, or little, responsive, it shows, on the contrary, unmistakable signs of strong resonances with the bar. For both models, the strongest resonance is CR, which proves to be much stronger in the halo than in the disk component. In fact, the CR peak in the halo of model MH is higher than any of the disk peaks in MD. There are also sizeable peaks at the OLR.

There are important differences between the orbital structures of the MH and MD halos, as was the case for the corresponding disks. The ILR peak of model MH is relatively high—the second highest peak for this model and time—and, in general, there is considerably more material between ILR and CR than in model MD, while the CR peak is 40% higher in model MD. All these are in agreement with the fact that the MH halo is much more concentrated than the MD one, while the MH corotation is at a larger radius. For smaller values of $R$, the situation shifts and the peaks are stronger for the MD case. The OLR peak of model MD is more than 1.8 times as high as the MH one, and the $-1:1$ peak is also clear in MD, while for model MH this resonance and its surroundings have been depleted.

The relative and absolute heights of the resonance peaks
vary with time. However, a large fraction of the orbits that are within a resonance peak at a given time continue to be so at a later time. Thus, comparing times 500 and 560, I find that 60%–80% of all orbits in one of the main resonant peaks at time 500 are found in the same peak at time 560. Similar numbers can be found by comparing times 800 and 860, except for the CR peak of the halo in the MH simulation, where the fraction falls to 55%. Given the uncertainties in delimiting the extent of a frequency peak, and the uncertainties in the calculation of the frequencies, these numbers are compatible with a large trapping of particles in the resonances. A more detailed description of these changes, together with a discussion of their effect on the structure and the dynamical evolution of the galaxy, will be given elsewhere.

4. DISCUSSION

In the above, I compared three simulations starting off with disks identical in mass and $Q$ but different halo components. Any differences in their dynamical evolution should thus be attributed to the halos. The strongest bar forms in the most halo-dominated case, provided this is live, while the simulation with an identical but rigid halo forms only a mild oval distortion, in the inner parts only. This very big difference can be attributed only to the responsiveness of the halo. The disk-dominated case, i.e., the case with the less important halo component, formed an intermediate bar. I thus reach the interesting conclusion that halos can, at least in some cases, stimulate the bar instability and lead to stronger bars.

Lynden-Bell & Kalnajs (1972) have shown that disk stars at resonances can absorb or emit angular momentum, thus driving the dynamical evolution. Halo stars in resonance can also exchange energy and angular momentum (Tremaine & Weinberg 1984). In general, the halo resonances will absorb angular momentum. Prompted by such considerations, I searched for resonant stars in the halo and found large numbers (at least after the bar has grown). Since these can exchange energy and angular momentum with disk resonant stars, they can stimulate the bar instability, contrary to previous beliefs, and thus explain why stronger bars can grow in more halo-dominated surroundings. The situation is particularly clear in the case of model MH, where, as Figure 2 shows, there are hardly any absorbers in the disk to take the angular momentum emitted by the stars at the ILR. This task is thus necessarily performed by the halo resonant stars.

Since the bar is inside corotation, it has negative energy and angular momentum (e.g., Lynden-Bell & Kalnajs 1972), and if it emits angular momentum it will be destabilized; i.e., it will in general grow stronger. This is in good agreement with the results on angular momentum transfer discussed at the end of § 2. These show that the halo takes positive angular momentum from the disk/bar component and, since the disk, the bar, and the final halo component all rotate in the same direction, this will destabilize the bar.

In the initial phases of the evolution, the bar grows faster in the disk-dominated surroundings, in good agreement with previous results (e.g., Athanassoula & Sellwood 1986). However, eventually, the bar in the MH model reaches a higher amplitude, owing to the stronger exchange of energy and angular momentum with the resonant halo stars. Thus, a massive halo may help the bar grow and become very strong, so that very strong bars may be found in initially halo-dominated galaxies. In other words, there is no disagreement between the results of, e.g., Athanassoula & Sellwood (1986) and those presented here or in AM or in Athanassoula (2002a, 2002b).

Hernquist & Weinberg (1992) checked the angular momentum given to a live halo by a rigid bar turned first on and then off adiabatically. In spite of considerable noise, they found indications that the angular momentum was deposited primarily at the resonances and that it is mainly absorbed. This tentative result is clearly established here; where both the disk and the halo are live, the evolution is not artificially forced and the resonances are clearly outlined.

In the linear theory, the exchange of energy and angular momentum is linked with the growth of the wave. In the nonlinear theory, on the other hand, it has been linked to the slowdown of the bar (Tremaine & Weinberg 1984; Weinberg 1985; Hernquist & Weinberg 1992). Both effects are clearly visible in the simulations presented here and should be physically linked.

The orbital structures revealed in Figure 2 are not specific to the models discussed above. I have repeated a similar analysis for other times and other simulations and found similar behaviors. They should thus be representative of a wide class of models.

I am thus proposing a new instability mechanism, by which the halo will stimulate, rather than restrain, bar growth. This of course will work only if the halo is nonrigid and is capable of absorbing positive angular momentum. Similarly, the bar should also be nonrigid. Further analysis of this mechanism will be given elsewhere.

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