New Results on Bar-Halo Interactions

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Abstract. In this paper I argue that, far from necessarily hindering bar formation in disc galaxies, inner haloes may stimulate it. This constitutes a new instability mechanism by which bars can grow. To show this I use a number of N-body simulations whose initial conditions have identical discs and more or less concentrated haloes. They show that the bar that grows in the more halo-dominated environment is considerably stronger than the bar that grows in the more disc-dominated environment. This result is obtained from simulations with live haloes, i.e. composed of particles which respond to the disc and take part in the evolution. On the other hand, if the halo is rigid, it hinders or quenches bar formation, as expected. Comparison of two simulations which are identical in everything, except that the halo is live in the first one and rigid in the second one, leads me to suggest that the halo response can help the bar grow. Following the orbits of the stars in the halo, I find that a considerable fraction of the halo particles are in resonance with the bar. The halo may thus take angular momentum from the bar and stimulate its growth. I finally discuss whether and how the results of the N-body simulations can be applied to real galaxies.

1. Introduction

It is by now well established that galactic discs can be bar unstable (e.g. Miller, Prendergast & Quirk 1970; Hohl 1971). In the quest for stability three main stabilising mechanisms have been proposed (see e.g. reviews by Athanassoula 1984, Sellwood & Wilkinson 1993 and references in either):

i) The disc could be immersed in a massive spheroid, e.g. a bulge and/or an inner halo (Ostriker & Peebles 1973).

ii) The disc could be hot or have a hot center (Athanassoula 1983, Athanassoula & Sellwood 1986).

iii) The galaxy could be sufficiently centrally concentrated to stop the initially linear wave from reaching the center (Toomre 1981; Sellwood & Evans 2001).

Each one of these mechanisms has generated a lot of discussion, both regarding its efficiency and the way it can be applied to real galaxies. Here I will address the first of them, which was also historically the first to be introduced, and show that, contrary to what has been argued so far, inner haloes can, at least in some cases, enhance the bar. For this I will use a series of numerical
Figure 1. Circular velocity curves of the three models discussed in section 2 (solid lines). The contribution of the disc component is given by a dashed line, and that of the halo by a dotted line. The left panel corresponds to simulation MD, the middle one to MH and the right one to RH.

simulations of disc-halo systems, described by Athanassoula & Misiriotis (2002, hereafter AM02) and Athanassoula (2002b in preparation, hereafter A02b). I describe the simulations and their results in section 2, and in section 3 I discuss the role of the halo. Finally in section 4 I give a general discussion and address the applicability of my results to real galaxies.

2. Simulations of and results on bar formation

I will present here the results of three $N$-body simulations made with the GRAPE-5 systems of Marseille observatory (Kawai et al. 2000). The three initial conditions have identical exponential discs of unit mass and scale length, and $Q = 1.2$. Their halos are five times as massive as their discs and have different degrees of central concentration. They are initially thermalised, spherical and non-rotating. The halo of the first simulation has initially a mass of 0.4 within three disc scale lengths, while the halo of the other two has a mass of 1.4 within that distance. The initial circular velocity curves (loosely called hereafter rotation curves) of the three models are shown in Fig. 1. In the first simulation, hereafter MD, the disc dominates in the inner parts, roughly up to $r = 5$, whereas in the other two (hereafter MH and RH, respectively), the halo contribution is slightly larger than that of the disc up to the maximum of the disc rotation curve, and considerably so after that. Model RH is identical to model MH, except that its halo is rigid – i.e. given by a potential imposed on the disc particles – and does not evolve during the simulation. Models MD and MH are similar to the ones described in AM02, but have somewhat thinner discs. Details on the initial conditions and on the simulations, as well as results for other such simulations, can be found in AM02 and in A02b. A reasonable calibration (AM02) gives that $t = 500$ corresponds to $7 \times 10^9$ years. Different values, however, can be obtained for different scalings of the disc mass and scale length.

The results of the evolution at $t = 600$ are summarised in Fig. 2. The upper row of panels gives the three “rotation curves”. We note that the disc material has moved considerably inwards in the two first cases, but much less so in the third one. In model MD the difference between $t = 0$ and $t = 600$ is quantitative, since the inner parts were initially disc dominated and are still
Figure 2. Results of the three simulations at $t=600$. The left panels correspond to model MD, the middle ones to model MH and the right ones to model RH. The upper panels give the “rotation curves” (solid lines), together with the contribution of the disc (dashed lines) and halo (dotted lines) components. The next three rows give the isodensities of the disc component when seen face-on (second row) and edge-on (third and fourth row). In the third row the bar is seen side-on and in the fourth row end-on. The last row gives again the face-on view of the disc component, but now as a dot plot. The size of the square box for the second and fifth row of panels is 10 initial disc scale lengths, and all panels, except for the upper row, have the same linear scale.
so after the evolution, albeit to a larger degree. On the other hand for model MH the difference is qualitative, since the inner regions are now dominated by the disc, contrary to what was the case initially. The remaining panels give the face-on, side-on and end-on views of the disc/bar component. The differences between the three models are striking. Comparing models MD and MH we note that the bar that grew in the initially more halo dominated environment is stronger than the bar that grew in the disc dominated environment (AM02). It is longer and its isophotes are more rectangular-like (AM02). Comparing the Fourier components, the surface density profiles and the isophotal shapes of the N-body bars with those of observed barred galaxies, I find that the MD-type bars have observed properties reminiscent of those of late-type bars, while MH-type bars resemble early-type strongly barred systems (Athanassoula 2002a).

Very strong differences can also be found when we compare model MH with model RH. Model MH has a very strong bar, while model RH has a mild oval distortion, or a very weak bar. The difference between the lengths of the two bars is striking – the MH bar being 2 or 3 times longer than the RH “bar”. Their edge-on views are also very different. Model MH seen side-on has a strong peanut or X-shape, and a big bulge-like protuberance if seen end-on. Model RH shows no such features.

The difference between the three bars is also clear when I plot the relative Fourier component of the face-on distributions of the discs (e.g. AM02). The maximum values of the relative $m = 2$ component for models MH, MD and RH at time 800 are 0.68, 0.45 and 0.23, respectively.

The three models differ also in the way their bars evolve. The pattern speed of model MH starts off higher than that of model MD, but ends considerably smaller. The pattern speed of MD also decreases with time, but much less so. In this our results agree at least qualitatively with those of Debattista & Sellwood (1998) obtained for different galactic models and with a different type of code. A more quantitative comparison, including the time evolution of the ratio of the corotation radius to the bar length, is underway. The pattern speed of the “bar” in RH can not 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 disc and halo components, so that the halo, which was initially non-rotating, displays rotation after the bar has grown. This is small for model MD and considerable for model MH, for which shortly after $t = 800$ the halo has roughly a third of the angular momentum of the disc, i.e. a quarter of the total.

3. The role of the halo

What is the role of the halo in these simulations, and why is it that the discs which are immersed in more massive live haloes make stronger bars? Although I still do not have a full quantitative answer to this question, I will present here results which can bring useful qualitative understanding.

I have always found that understanding the orbits in a given system is a crucial step towards understanding its dynamics. In particular Lynden-Bell & Kalnajs (1972) have shown that stars at resonances can absorb or emit angular momentum, thus driving the evolution of the disc. I therefore froze the potential
Figure 3. Number density of disc particles as a function of the frequency ratio $(Ω - Ω_p)/κ$, for simulation MD (upper panel) and MH (lower panel) at $t = 800$. The dot-dashed vertical lines give the positions of the main resonances.

at a few selected times during each simulation and followed the orbits of 100 000 disc particles, and of an equal number of halo ones. From these I calculated the basic frequencies of each orbit, namely $Ω$, $κ$ and $κ_z$. Here $Ω$ is the angular frequency, $κ$ is the epicyclic frequency and $κ_z$ is the vertical frequency. An orbit is resonant if there are three integers $l$, $m$ and $n$ such that $lκ + mΩ + nκ_z = mΩ_p$, where $Ω_p$ is the pattern speed of the bar.

The main resonances occur for small integer numbers. 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 $m = 2$, the corotation resonance (CR), where $l = 0$, the outer Lindblad resonance (OLR), where $l = 1$ and $m = 2$, and the inner and outer ultra-harmonic resonances (IUHR and OUHR respectively), for which $m = 4$ and $l = -1$ and 1 respectively. At corotation resonance the particles have the same angular frequency as the bar, while in the other resonances they make $m$ radial oscillations in the time they make $l$ revolutions around the center of the galaxy. Calculating the basic frequencies, and in particular $Ω$, is far from straightforward. In fact I am still working towards an optimum method, combining reliability, robustness and speed, so that the results given here can be considered as somewhat preliminary. Nevertheless, they are sufficiently reliable for 80% to 90% percent of the particles and so they warrant discussion.

Figures 3 and 4 show the number density of particles/orbits that have a given value of $(Ω - Ω_p)/κ$ as a function of this ratio. Let me first describe the results for the disc components. The distribution is far from homogeneous
Figure 4. Number density of halo particles as a function of the frequency ratio \((\Omega - \Omega_p)/\kappa\), for simulation MD (upper panel) and MH (lower panel) at \(t = 800\). The dot-dashed vertical lines give the positions of the main resonances.

and there are strong peaks at the location of the main resonances. The highest peak, both for the MH and the MD disc, is for the ILR, where \((\Omega - \Omega_p)/\kappa = 0.5\). 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. The peak is higher, by roughly 60 %, in the MH case than in the MD case, in agreement with the fact that the bar in this model is stronger (cf. Fig. 2). The height of the CR peak is sizeable for model MD, and small for MH. The ratio of the height of the CR peak to that of the ILR is 0.47 for the MD case, while for model MH it is only 0.09. Model MD has a sizeable peak also for \((\Omega - \Omega_p)/\kappa = -0.5\), i.e. at the OLR. The differences between the two models are due to their different corotation radii. Thus at time 800 the CR radius is 6.7 for model MH and 3.3 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 disc 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.

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. Since we have analysed the same number of particles from the two components, while there are roughly five times more halo than disc particles, the halo numbers should be multiplied by roughly five, thus highlighting the importance of the halo for the dynamical evolution of the galaxy.
There are important differences between the orbital structures of the MH and MD haloes, as was the case for the corresponding discs. The ILR peak of model MH is relatively high (more than 20 times higher than the corresponding MD peak) and there is considerably more material between ILR and CR than in model MD, while the CR peak in model MH is more than twice as high as the corresponding peak in model MD. All these are in agreement with the fact that the MH halo is much more concentrated than the MD one. Further out the situation shifts. The OLR peak of the MD model is more than twice as high as the MH one, and the -1:1 peak is also very high in MD, while for model MH this resonance has been depleted of its particles. The amplitude of the CR peak for model MD shows considerable evolution with time, nearly doubling from 500 to 800. The role of these differences in the dynamical evolution of the galaxy will be discussed elsewhere.

Halo stars in resonance with the bar can exchange energy and angular momentum with it and thus influence its evolution (Tremaine & Weinberg 1984). In general, the halo resonances will absorb angular momentum. Since the bar is inside corotation, it has negative energy and angular momentum, and thus the effect of halo resonant stars will be to destabilise it, i.e. will lead to stronger bars. This is in good agreement with the results on angular momentum transfer discussed at the end of the last section. Since the disc, the bar and the final halo component rotate in the same direction, the halo will take positive angular momentum from the disc/bar component and thus will further destabilise the bar.

I am thus proposing a new instability mechanism, by which the halo will stimulate bar growth. This of course will only work if the halo is non-rigid and is capable of absorbing positive angular momentum. Similarly the bar should also be non-rigid. Further work quantifying this mechanism and studying its efficiency in different types of models and in real galaxies is in progress (A02b). An analytical description of this instability, including the effect of the non-planar resonances, and a comparison with the N-body results is forthcoming, in collaboration with M. Tagger and F. Masset.

4. Discussion

In the above I have compared three simulations starting off with identical discs, but different halo components. Any differences in their dynamical evolution should thus be attributed to the haloes. The strongest bar forms in the most halo dominated case, provided this is live, followed by the one in the disc-dominated case. In the simulation with the rigid halo there is only a very weak bar, or mild oval distortion, in the inner part. I thus reach the interesting conclusion that haloes can, at least in some cases, stimulate the bar instability and lead to stronger bars. This can be understood by a frequency analysis of the halo orbits, which reveals a large number of resonant orbits. Since these can exchange energy and angular momentum with stars at other resonances (Lynden-Bell & Kalnajs 1972) they can stimulate the bar instability, contrary to previous beliefs.

The evolution of the galaxy leads to considerable concentration of the disc material in the central areas. Thus model MD starts off as disc dominated in the central parts, and, with time, the disc further enhances its superiority. Model
MH starts off quite differently. Initially the halo is slightly more important than the disc within the radius at which the disc rotation curve is maximum, and considerably more so at larger radii, as witnessed from its circular velocity curve, shown in Fig. 1. The central concentration of the disc increases considerably with time, so that, after the bar has grown, the disc dominates in the inner region. This may contribute an additional argument to the long standing debate of whether galactic discs are maximum or sub-maximum (e.g. Athanassoula, Bosma & Papaioannou 1987; Bosma 1999, 2000; Bottema 1993; Courteau & Rix 1999; Kranz, Slyz & Rix 2001; Sellwood 1999, Weiner, Sellwood & Williams 2001).

Sackett (1997) and Bosma (2000) give a simple working definition to distinguish between maximum and sub-maximum discs, based on the value of $\gamma = V_{d,\text{max}}/V_{\text{tot}}$, where $V_{d,\text{max}}$ is the circular velocity due to the disc component and $V_{\text{tot}}$ is the total velocity, both calculated at a radius equal to 2.2 disc scale lengths. According to Sackett (1997) this ratio has to be at least 0.75 for the disc to be considered maximum or maximal. In the simulations it is not easy to define a disc scale length after the bar has formed, so I will calculate $\gamma$ at the radius at which the disc rotation curve is maximum, which is a well defined radius and is roughly equal to 2.2 disc scale lengths in the case of an exponential disc. Model MD starts off with $\gamma > 0.75$, so that the disc starts maximum and stays so all through the simulation. In fact the value of $V_{d,\text{max}}/V_{\text{tot}}$ increases somewhat with time. Model MH has initially a value of $\gamma$ around 0.68, i.e. close to the value of 0.63 advocated by Bottema (1993), and is therefore initially sub-maximum. This value, however, increases abruptly after the bar has formed, so that the disc can be considered maximum well before the time shown in Fig. 2, with a value of $\gamma$ roughly equal to 0.86. Thus the formation of the bar leads the disc to evolve from sub-maximum to maximum, and hence strongly argues for maximum discs in disc galaxies with strong bars. This means that if we observe a strong bar in a disc galaxy the above simulations argue strongly and quantitatively that the underlying disc is maximum. The existence of gas should not alter this result. Indeed if the gas leads to a density distribution with a weak bar or no bar, then the above argument will be irrelevant, since it applies only to galaxies with strong observed bars. On the other hand, if the resulting bar is strong, then it should have rearranged the disc material sufficiently for the above argument to hold.

We can reach similar results about the disc-to-halo mass ratio if we use the criterion of Athanassoula, Bosma & Papaioannou (1987), who examined what spiral perturbations can grow in a given disc/halo decomposition of an observed rotation curve. In a similar way I can calculate the $m$ component that will be strongest amplified via the swing amplification mechanism (Toomre 1981) in my simulations at or around the radius at which the disc rotation curve reaches its maximum. I find that, for model MD, it is the $m = 2$ all through the simulation, as expected. The initial disc for model MH is certainly not maximum. I find that at $t = 0$ higher $m$ components will be the most strongly amplified. The evolution, however, changes this, so that after the bar has grown it is the $m = 2$ component that is the strongest amplified at or around the radius at which the disc rotation curve reaches its maximum. Both MD and MH models thus have, after the bar has grown, a disc which is intermediate between the “no $m = 1$” and “no $m = 2$” limits advocated by Athanassoula, Bosma & Papaioannou
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(1987) for real galaxies. Indeed these authors made a link between the structure present in a disc at a given time and the underlying halo mass at that time (not the initial halo mass) and thus their results are in good agreement with the above simulations, and many other similar ones (e.g. AM02 and A02b).

Apart from the halo, several other parameters can influence the formation of a bar. In particular let me stress the importance of the velocity dispersion of the disc particles, the effect of gas, and the effect of the velocity and mass distribution in the halo, as well as the existence of a gaseous companion. A complete description of all these effects is well beyond the scope of the present contribution and will be presented elsewhere. Let me just add a few preliminary words about the effect of the disc velocity dispersion. A sequence of MH-type galaxies shows that for larger initial velocity dispersion of the disc particles the bar is less strong and for sufficiently high values, becomes oval, or quasi-circular, in good agreement with what was found for 2D models (Athanassoula 1983). A sequence of MD-type models is more complicated. In these models the bar grows faster and becomes very long and strong. At that time, however, a strong buckling instability develops which leads to a considerable decrease of the bar amplitude. The final amplitude of the bar is a result of the competition between these two effects and this may be close. Only at sufficiently large values of the velocity dispersion can we be sure that the resulting oval will be very thick, as in the MH sequence. All the above are rather preliminary and will be discussed at length elsewhere.

Finally the mass and velocity distribution of the halo component, together with the bar pattern speed and its time dependence, should influence how each of the resonance regions is populated and how responsive it is, and therefore influence its ability to exchange energy and angular momentum with the bar. Since very little is known on the composition of the halo, let alone about the distribution of the matter in it, it is very difficult to pursue this issue further. Nevertheless the arguments in section 3 lead to the prediction that at least some of the stars of the visible halo should be in resonance, in as much as they trace the relatively inner parts of the halo. Testing this would necessitate accurate information on the six phase space coordinates of a sufficiently large number of halo stars, as well as a sufficiently accurate description of the halo potential and the bar pattern speed. Our own Galaxy, which is barred, is the only place where advances with future astrometric satellites may make this possible, if we concentrate in areas which could have a high fraction of resonant stars.

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Discussion

Kormendy: You concluded that disks of barred galaxies are maximal. Ortwin Gerhard concluded in the previous talk that the disk of our Galaxy is close to maximal. But Piet van der Kruit concluded that the typical late-type disk is substantially sub-maximal. This is a microcosm of the debate about maximal
versus sub-maximal disks that has been going on in the literature for a long time. I wonder what we can learn about this apparent disagreement and in particular whether we can make progress in resolving it because we have proponents of both points of view at this meeting.

Athanassoula: My simulations show that even discs which are initially sub-maximum can form bars and thus evolve to maximum. They thus argue that discs with strong bars are maximum, or near so. Concerning non-barred galaxies there are, as you just said, results arguing for maximum discs and others arguing for sub-maximum discs. I thoroughly agree that a debate on this subject would be most useful and I would like to mention that it will be the topic of a panel discussion in the 6th Guillermo Haro meeting, which will take place in Puebla (Mexico) in November 2001.

Illingworth: What are the initial conditions for your models? I am wondering how you would relate these to actual galaxies. In a sense, how realistic are they compared to how galaxies are built up?

Athanassoula: The instability mechanism which I proposed here, namely stimulating the bar growth by its interaction with the halo, depends on the present day properties of the halo and the bar, and only indirectly on the formation history of the galaxy. Since the properties of my $N$-body bars are in good agreement with those of bars observed at $z = 0$, I do not have to worry overly about how the galaxy was built up, at least in as much as the physics of the mechanism I proposed here is concerned. Of course if we were able to follow the formation of discs and bars starting from initial conditions resembling those of galaxies observed at high $z$, including a fair fraction of gas and non-equilibrium initial conditions, we would be able to learn a lot about disc galaxy formation and evolution.