Dark Matter in Galaxies
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Bars and the connection between dark and visible matter

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Abstract. Isolated barred galaxies evolve by redistributing their internal angular momentum, which is emitted mainly at the inner disc resonances and absorbed mainly at the resonances in the outer disc and the halo. This causes the bar to grow stronger and its pattern speed to decrease with time. A massive, responsive halo enhances this process. I show correlations and trends between the angular momentum absorbed by the halo and the bar strength, pattern speed and morphology. It is thus possible to explain why some disc galaxies are strongly barred, while others have no bar, or only a short bar or an oval. In some cases, a bar is found also in the halo component. This "halo bar" is triaxial, but more prolate-like, is shorter than the disc bar and rotates with roughly the same pattern speed. I finally discuss whether bars can modify the density cusps found in cosmological CDM simulations of dark matter haloes.

1. Introduction

It is impossible to observe dark matter directly, but its existence and a number of its properties can be deduced from its effects on other, visible, galactic components. Thus, properties of the disc and of its substructure can, if correctly interpreted, give us clues on the properties of dark matter haloes. Here I will discuss the connection between bars and dark matter, and what information the former can give us on the latter.

2. Angular momentum exchange. Analytical results

The growth of bars in isolated disc galaxies is governed by the exchange of angular momentum between different parts of the galaxy. To understand this better it is best to start with the pioneering paper of Lynden-Bell & Kalnajs (1972; LBK). Using linear analytic theory, these authors showed that it is mainly material at resonance that gains or loses angular momentum. Material at the inner Lindblad resonance (ILR) will lose angular momentum, while material at corotation (CR) and the outer Lindblad resonance (OLR) will absorb it. Since the spiral/bar within CR is a negative angular momentum perturbation, feeding it with angular momentum will damp it, while taking angular momentum from it will excite it. Following in their footsteps, Athanassoula (2003; A03) added a halo (or, more generally, a spheroidal component) and applied the results to the case of bars. Provided the halo distribution function is a function of the energy only, halo material at *all* resonances will gain angular momentum. This result should be generalisable to other distribution functions, provided energy is the main functional dependence and an appropriate perturbation expansion can be used. Both for the disc and for the halo, there is more angular momentum lost/gained at a given resonance if the density is higher there and if the resonant material is colder and thus more responsive (A03).

So, if a disc galaxy has no halo, or if the latter cannot participate in the angular momentum exchange, the inner disc will emit angular momentum, which will be absorbed by the outer disc. On the other hand, if a halo is present and responsive, then it also will absorb angular momentum. So more angular momentum can be extracted from the inner parts in the presence of a responsive dark matter halo and the bar will grow stronger than in its absence (A03). This explains the 'paradox' that bars in halo dominated disc galaxies may grow stronger than in disc dominated cases (Athanassoula & Misiriotis 2002; AM02).

Tremaine & Weinberg (1984) and Weinberg (1985) used nonlinear theory to follow the effect of angular momentum exchange on the slowdown of the bar. They find that, as the bar loses angular momentum, it will slow down, as expected. These works, put together with the analytical studies discussed above, lead to the firm prediction that bars should become stronger and rotate slower in the presence of massive and responsive haloes.

3. Angular momentum exchange. Simulation results

In Athanassoula (2002; A02) and A03 I tested the above analytical results with the help of N-body simulations and I will follow the same path here. The first point to test is that there are indeed stars at (near-) resonance in the halo and that they absorb angular momentum, as predicted by the analytical results. This is shown in Fig. 1, which has been obtained as described in A02 and A03. The upper panels plot the mass per unit frequency ratio, M_R, as a function of that frequency ratio, namely $(\Omega - \Omega_p)/\kappa$. Here Ω is the angular frequency, κ is the epicyclic frequency and Ω_p is the bar pattern speed. These panels show that the distribution is not at all uniform, but has strong peaks at the resonances. This is true both for the disc, as expected, but also for the halo, as shown initially in A02. The lower panels show the change of angular momentum with time (A03), again as a function of the frequency ratio. Note that the theoretical predictions of LBK, as well as those of A03, are well confirmed by the above results, since these show that a large fraction of both the disc and the halo particles are at resonance, and that they emit/absorb angular momentum, as predicted.

I next check how important the effect of the resonances is. This can be seen in Fig. 2, where I compare the face-on view of the results of three simulations. Initially, the leftmost is disc dominated in the inner parts, or, in the notation of AM02 and A03, it is of MD-type. On the contrary, the simulation shown in the middle panel has initially a large relative halo mass in the inner parts, i.e. it is of MH-type. Finally, the simulation at the right is initially exactly the same as the previous one, except that the halo is rigid (RH). In this case, the halo is only present as a rigid potential, so it can not participate in the angular momentum exchange. The difference between the middle and right panels is indeed stunning! Instead of the strong bar of the MH case, the RH case displays

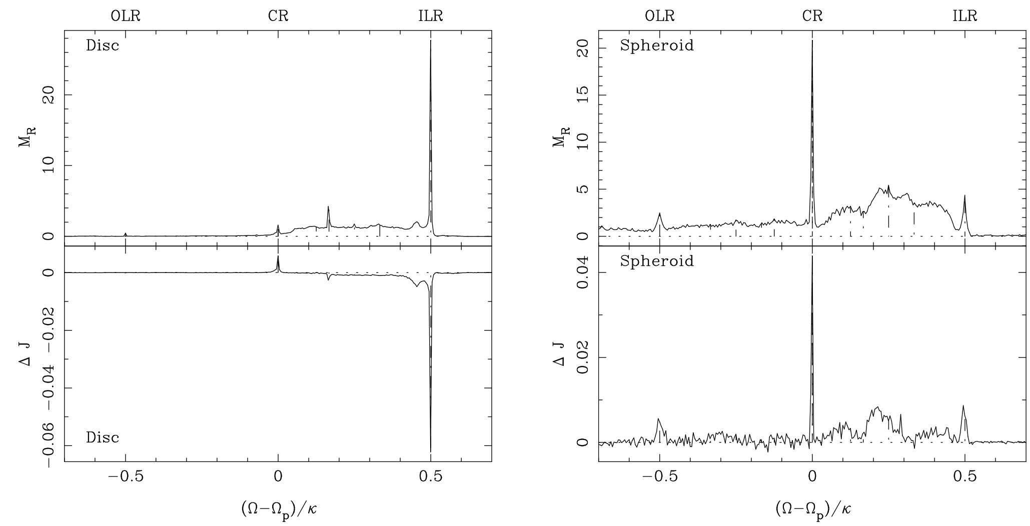

Figure 1. Resonances and angular momentum exchange. The upper panels give the mass per unit frequency ratio as a function of that ratio at a time towards the end of the simulation. The lower panels give ΔJ, the angular momentum gained, or lost, by the particles between two times, both taken after the bar has formed, again as a function of the frequency ratio. The left panels correspond to the disc and the right ones to the spheroid. The vertical dash-dotted lines give the positions of the main resonances.

a short oval, confined to the inner parts. Furthermore, comparing the left and middle panels one can clearly see that the strongest bar has grown in the most halo dominated environment. These comparisons, and many others in AM02, A02 and A03, argue strongly for the role of resonances in bar evolution.

Theory predicts that both the amount of mass at resonance and its velocity dispersion should influence the amount of angular momentum exchanged, and therefore the bar strength and the pattern speed decrease. A03, with the help of appropriate sequences of simulations, showed this to be indeed true in the case of N-body simulations. Thus, the increase of the bar strength and the decrease of its pattern speed are jointly set by three factors : the relative amount of halo mass at (near-) resonance, how hot the disc is at the resonances, and how hot the halo is at the resonances. Any one on its own is not sufficient to determine the outcome, since all three can limit the amount of angular momentum exchanged.

Since the amount of angular momentum exchanged is a determining factor, one expects to find correlations between this quantity and the bar evolution. Unfortunately, the angular momentum exchanged is a difficult quantity to measure, so in Fig. 3, as in A03, I use instead the total angular momentum gained by the halo, relative to the total angular momentum initially in the system. This, however, is a good approximation of the total angular momentum exchanged only in cases when the outer disc absorbs only little angular momentum. Even so, Fig. 3 shows, for a very large number of simulations, a clear correlation between the relative amount of angular momentum absorbed by the halo and the

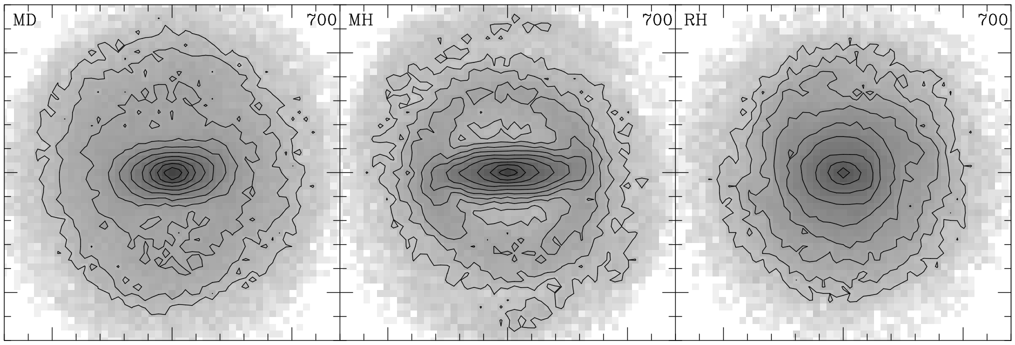

Figure 2. Effect of the halo on bar evolution : Face-on views of the results of three simulations with different halo components.

bar strength, as well as a trend between it and the bar pattern speed. Furthermore, if I limit myself to simulations where the halo is the main absorber (lower panels), then the latter trend becomes a very strong correlation (middle lower panel). These results are basically the same as those shown in A03, except that I have added here a few more simulations, which have been run since that paper was written.

How much are the above correlations dependent on the particular type of initial conditions used? It is reasonable to assume that initial conditions having different density and velocity profiles for the disc, bulge and halo component will also give such correlations, since these correlations are the reflection of the physics underlying bar evolution. However, it could well be that the regression lines (or loci defined by the trend) are somewhat differently located (shifted) on the corresponding planes. That can be properly tested only by repeating this type of work with different initial models; a rather daunting task seen the very large number of simulations necessary. Yet a few clues exist already. For example, from the middle lower panel one can see that the regression line is somewhat shifted to the right for simulations with a more concentrated spheroidal. Similarly, the right bottom panel shows that the regression line is somewhat lowered for simulations with initially hotter discs. The differences, however, are rather small, and one can conclude that more angular momentum exchange will lead to stronger bars that rotate slower.

Berentzen et al. (2003) present a study where the bar is driven by a companion in a disc in which a previous bar had been destroyed by gas inflow. They find good agreement of the results of their simulations with those presented here on the (S_B, Ω_p) plane, even though the initial models and particularly the problem at hand are very different.

How does the amount of angular momentum exchanged influence the morphology of the bar? Fig. 4 shows the results of three simulations. In the one shown in the left panel a large amount of angular momentum was exchanged during the evolution. It has a strong bar, as is the case for all such simulations. The middle and right panels show examples from simulations where little angular momentum has been exchanged. In the middle one, the disc is initially hot and the halo is relatively cool and concentrated. Thus the outer disc can

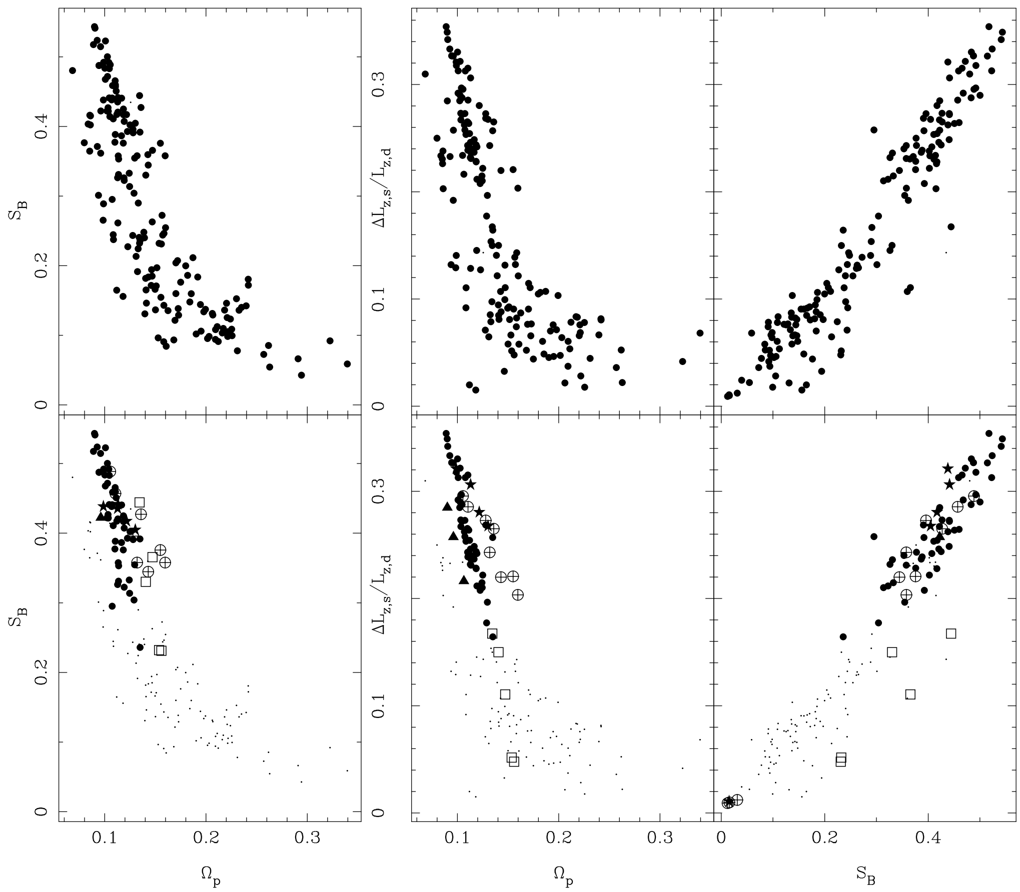

Figure 3. Relations between the strength and the pattern speed of the bar (left panels), between the fraction of the total angular momentum in the spheroid and the bar pattern speed (middle panels) and between the same quantity and the bar strength (right panels). Each symbol represents the result of one simulation (A03). In the lower panels, results of simulations with a small initial halo core radius are given with a large symbol, while those with a large core radius with a dot. In particular, simulations with bulges are marked with a $\oplus$, while filled triangles, filled circles and filled stars denote simulations with different initial core radius, in order of increasing concentration (see A03). Finally, open squares are for simulations similar to those denoted by filled circles, but which have initially very hot discs.

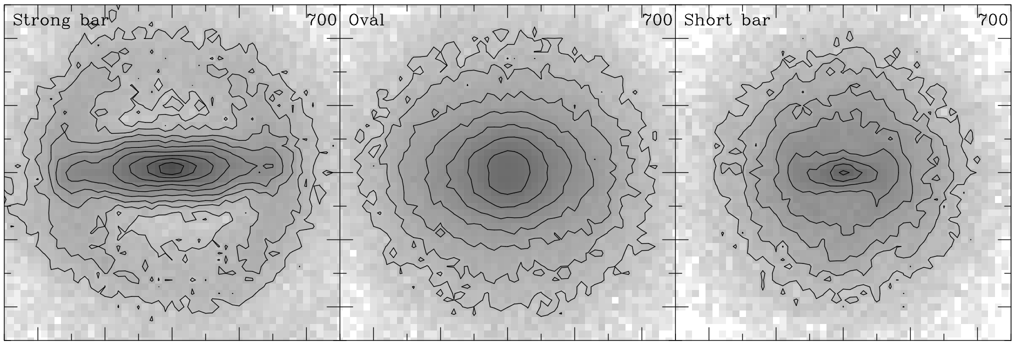

Figure 4. Effect of the amount of angular momentum exchanged on the morphology of the galaxy : Face-on view of the results of three simulations in which different amounts of angular momentum have been exchanged between different parts of the galaxy.

not contribute much to the angular momentum exchange and it is the halo that absorbs most of the angular momentum. The result is an oval, which extends to large radii, in order to maximize the emitting region. In the last example (right panel) the halo is very hot, so it can not absorb much angular momentum, while the disc is initially relatively cool. Thus the bar has to stay short, in order for its CR and OLR to be in regions of relatively high density, so as to contribute an efficient angular momentum sink. To summarize, one can say that cases where a lot of angular momentum has been exchanged always display strong bars. On the other hand, in cases where only little angular momentum has been exchanged, the bar can either be short, or longer but more like an oval, depending on whether it is the disc or the halo that is the main absorber.

4. Why is there such a wide variety of bar strengths in observed galaxies, and why are some galaxies non-barred ?

Observed bars come in a wide variety of strengths, ranging from very strong bars, like NGC 4608 (Gadotti & de Souza 2003) or NGC 1365, to short bars, like our own Galaxy, or ovals, like in NGC 1566. Furthermore, a few discs have no bar at all (Grösbol, Pompei & Patsis 2002). How does that compare with the N-body results?

Haloes were initially thought to stabilise discs (e.g. Ostriker & Peebles 1973). More recent work (AM02, A02, A03) shows that this statement is not necessarily correct, since haloes can stimulate bar growth by taking angular momentum from the inner disc. Nevertheless, bars forming in disc galaxies with a substantial halo take *longer* to form than bars forming in galaxies with less halo, so that, in a sense, a halo can be considered as having a stabilising influence, although the bars that grow in a more massive and responsive halo may finally become stronger. A03 showed that this can happen for a wide range of halo to disc mass ratios, provided of course the halo is responsive. This, however, will not necessarily extend to very low relative disc masses (A03). Simulations to test this limit would be very CPU intensive, since they would necessitate a very large number of particles, and also because the bar growth would be exceedingly slow. Moreover, if the bar grows in time scales much longer than the Hubble time, the problem is of little astronomical interest and the corresponding galaxies can be considered bar-stable.

Haloes can have a further stabilising influence either if their mass distribution is such that not much material is at resonance with the bar, or, more likely, if the resonant halo material is very hot and thus can not absorb much angular momentum. Unfortunately, not much is known about the velocity distribution within the halo component in real galaxies.

Similarly, a bar forming in a hot disc will take longer to grow than in a cold one (Athanassoula & Sellwood 1986, A03). In very hot discs, when the bar eventually forms, it has the form of an oval (see Fig. 4).

Thus, with the help of N-body simulations, we can account for the large variety of bar strengths observed in real galaxies. As discussed also in the previous section, this will be determined by the total amount of angular momentum exchanged and also by the specific amount by which each of the partners (inner disc, outer disc, halo, bulge) enters in the exchange. In this picture, galaxies with no bars should have a very low relative disc mass and/or a very hot disc and/or a rather unresponsive halo, so that the bar takes very long to grow and so that the halo can not help its secular evolution.

This picture is not complete. There is still the question of black holes, and other 'extreme' central concentrations, which should have a stabilising influence. The interplay between this and the responsiveness of the disc and halo will be discussed elsewhere.

5. A bar in the halo

In cases with a sufficiently strong bar in the disc component, the halo does not stay axisymmetric, but shows also a bar-like or oval deformation. An example can be seen in Fig. 2 of Holley-Bockelmann, Weinberg & Katz (2003; HBWK). I found such structures also in my own simulations and I call them, for simplicity, halo bars. Preliminary results show that, in cases with a strong disc bar, the halo bar is triaxial, but prolate like, with axial ratios of the order of 0.7 or 0.8 in the inner parts, and becomes more spherical as the radius increases. The length of the halo bar increases with time, but always stays considerably shorter than that of the disc bar. It is roughly aligned with the disc bar at all times (at least within the measuring errors), i.e. it turns with roughly the same pattern speed. This means that it is a slow bar. The bisymmetric component in the halo extends well beyond the end of the halo bar, and there it trails behind the disc bar, much as seen in Fig. 2 of HBWK. The properties of these halo bars will be discussed in detail elsewhere (Athanassoula, in prep.).

6. Do bars flatten or steepen central halo cusps?

Current cosmological CDM simulations predict that dark matter haloes are cuspy (e.g. White, this volume), although there is still no agreement reached about the value of the inner slope. On the other hand, observations have shown that, at least in a number of cases where the data are of sufficiently good quality, haloes have cores (e.g. Bosma, or de Blok, this volume). If haloes were indeed formed with a cusp and now have a core, then some mechanism during galaxy formation and/or evolution should be responsible for this change. Several have been so far proposed, of which one involves a bar. Indeed, Hernquist & Weinberg (1992) and Weinberg & Katz (2002), based on analytical calculations and on N-body simulations of a cusped halo containing a rigid bar and no disc, proposed that the bar could flatten the cusp by giving angular momentum to the halo. This, however, was not generally accepted, since the fully self-consistent simulations of Sellwood (2003; S03) and Valenzuela & Klypin (2003; VK) showed the contrary, i.e. that during the evolution the halo radial profile showed a small, yet clear, steepening. These authors attribute the flattening found by the previous simulations to the fact that they do not include a live disc, and thus neglect the slow gradual change of the resonant positions due to the slowdown of the bar, and the disc responsiveness. This explanation did not, in turn, satisfy HBWK, whose fully self-consistent simulations showed a clear flattening of the halo cusp (HBWK) and thus argued that self-consistency, or the lack of it, could not be the factor determining why some of the previous simulations showed a flattening and others a steepening. HBWK instead argue that the cusp steepening found by S03 and VK is spurious, and due to the fact that their simulations are noisy and thus do not describe the resonances sufficiently accurately. Numerical noise could indeed, if sufficiently strong, prevent the halo resonances from absorbing the correct amount of angular momentum and thus lead to a wrong evolution. Other numerical shortcomings, however, e.g. leading to a wrong coupling between the planar and vertical resonances, could also influence the results, producing a spurious flattening or steepening.

Faced with the difficult task of reviewing this unsatisfactory state of affairs, I turned to my own simulations (AM02, A02, A03) to see whether they could provide any clues. They are neither grid based, nor use SCF, and thus could provide an independent view. They were not specifically designed to tackle this problem, so the initial halo has a core (albeit sometimes small). They can, nevertheless, lead to a number of insightful conclusions, which I will discuss briefly below. In particular, my study of the resonances allows me to single out and to follow the resonant stars. I could thus make sure that they cover the phase space adequately. Furthermore, in A02 I showed that there is a large trapping of the particles at resonances, which shows that they are not unduly knocked off their trajectories by noise during the evolution. Thus, my simulations fulfill all the necessary conditions set by HBWK to perform the test at hand.

In order to check whether the density profile in the inner parts flattens or steepens, I simply measured the amount of mass in concentric spherical shells[1]. Since the existence of a bar is necessary for the mechanism to work, I confined myself to times after the bar had grown. I find that, in the vast majority of the cases I checked, there is a steepening of the halo radial density profile, albeit not large. In a couple of cases, however, I noted a very small flattening. Since this

[1] Although very straightforward, this method is not the most appropriate for the problem at hand, because, as discussed in the previous section, the halo isodensities are triaxial and not spherical. Results based on other methods of calculating the density will be discussed elsewhere.

is even smaller in amplitude than the small steepening found in the remaining cases, I was ready to discard it as insignificant, until I noticed that it occurred in the more centrally concentrated cases. This prompted me to investigate the problem further.

The analytical predictions are clear and follow directly from what was discussed in the previous sections : Halo material at (near-) resonance should absorb angular momentum and move to larger cylindrical radii[2]. For the case of the ILR, such material is located in the inner parts of the halo and this should lead to a flattening of the cusp. I have already shown in the previous sections that my simulations confirm the theoretical predictions about the existence of the resonances and the angular momentum exchanged. Showing the increase of the cylindrical radius of particles on orbits at, or around, the ILR is no an easy task, since they are trapped around periodic orbits of the x_1 tree[3], for which it is not always easy to calculate the frequencies and the time average of the radius. Moreover, there are relatively few particles at ILR in the models I simulated (Fig. 1). On the other hand, it is very easy to see the increase in cylindrical radius in the case of CR, which does not suffer from the above drawbacks.

This, however, is not the complete picture, since there are three effects working against the previous one, and thus leading to a steepening of the halo :

- As stressed by AM02, VK and O'Neill & Dubinski (2003), the radial density profile of the disc becomes considerably more centrally concentrated with time. In so doing, the disc material pulls the halo material also inwards, thus causing it to contract. This leads to an increase of the halo radial density profile in the inner parts.
- As the halo gains angular momentum it will get flattened towards the disc equatorial plane and this will result in a decreasing of the spherical radius of the individual particles. As seen in the previous section, this happens mainly in the inner parts of the halo and will, therefore, lead to a steepening of the cusp.
- During the evolution the bar becomes stronger and this influences the shape of the periodic orbits of the x_1 tree and of the regular orbits trapped around them. Namely, their axial ratio a/b increases and they approach nearer to the center, so that sometimes the trapped orbits can actually cover the central area. This means that, although their average cylindrical radius may increase, the central-most area may have an increased density.

There are thus competing effects : On the one hand the resonant particles can move to larger cylindrical radii and thus tend to flatten the cusp. On the other hand, there are other effects, also linked to the angular momentum redistribution, which tend to diminish the spherical radii of the particles. It is the outcome of the competition between these effects that will decide whether the inner density profile will become steeper or shallower during the evolution. It

[2]It is important in this problem to distinguish between cylindrical and spherical radius.

[3]The x_1 tree is the 3D orbital analog of the 2D x_1 family and provides the backbone of the 3D bars (Skokos, Patsis & Athanassoula 2002).

is thus not necessarily surprising that HBWK find a flattening of the cusp, while S03 and VK find a steepening. The final result will depend on the distribution function of the halo, of which hardly anything is known, as well as that of the disc. In as far as the N-body simulations are concerned, it could also, unfortunately, depend on numerical effects, which could artificially modify the effect of the resonances.

The application of this mechanism to real galaxies faces, to my mind, two further serious problems. One is that haloes have substructure. Although this will not inhibit resonance driven evolution (Weinberg 2001), it could still perturb the effect of the resonances. The second, perhaps even more serious, problem is the presence of gas. All simulations that have so far studied this mechanism are purely stellar and have no gas. A gaseous component could increase further the central concentration of the disc material (e.g. Athanassoula 1992, Heller & Shlosman 1994) and thus make its inwards pull on the halo material yet stronger. It would then become yet more difficult for the halo (near-) resonant stars to overcome the inwards pull and achieve a flattening of the cusp.

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