Constraints on nested bars – implications for gas inflow

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Abstract. A wide-spread belief that nested bars enhance gas inflow to the galactic centre has recently been contradicted by dynamical models in which inner bars seem to prohibit such inflow. Can the existing models of dynamically possible double bars be modified to enable strong inflow in the secondary bar? I present here simple dynamical arguments which imply that in general, double bars in resonant coupling do not enhance gas inflow. However, stronger inflow with straight shocks in the inner bar can occur if there is no resonant coupling of the commonly assumed form between the bars.

1. Introduction

Any non-axisymmetric perturbation in mass distribution in the galactic disk exerts torques, which pull the disk matter out of circular orbits. The resulting trajectories, which often intersect, can be populated by stars, but gas clouds will collide and drop down the potential well. Thus in general, an asymmetric gravitational potential enhances gas inflow towards its central parts.

The most common asymmetry in the disk plane developed in unstable disks is an $m = 2$ bar-like mode. Various studies of gas flow in barred galaxies (see Athanassoula 2000 for a recent review) indicate that the gas transport into the central kpc differs from that within the central kpc. On large scale, two straight shocks develop on the leading edges of the bar, and gas falls towards the center along these shocks. Nevertheless, if the galaxy has an inner Lindblad resonance (ILR), the inflow may stagnate inside of it, with gas settling on the nuclear ring there. This mode of gas flow has importance for star-forming nuclear rings observed in barred galaxies. Recently, it has been found that when the cloud velocity dispersion is high enough, gas may avoid stagnating on the nuclear ring, and can flow inwards along a nuclear spiral (Englmaier & Shlosman 2000).

If another, smaller bar exists inside the ILR of the large-scale bar, and if gas flow in this secondary bar is analogous to the one in the main bar, then this secondary bar may force gas deeper into the potential well. This scenario is a modification of the fueling mechanism proposed by Shlosman et al. (1989), which originally involved gaseous bars. Rapidly increasing number of galaxies in which nested stellar bars have been seen (Laine et al. 2002) brought attention to this scenario. However, Maciejewski & Sparke (2000) showed that such double bars are unlikely to increase the inflow because of their orbital structure. Here I examine assumptions behind this last claim, and explore how to waive them.
2. The standard model of Maciejewski & Sparke (2000)

Since the two bars in doubly barred galaxies can be seen virtually at any relative orientation, they most likely rotate independently, each with its own pattern speed. Such double bars will not admit any closed periodic orbits in general, which served as a backbone of the steady potential of a single bar. In order to find regular stellar orbits supporting double bars, Maciejewski & Sparke (2000) assigned sets of test particles to imaginary closed strings that change shape as the bars rotate through each other, but return to their original positions after the two bars realign. They call these sets of particles *loops*, and if the loop remains aligned with one bar or the other, then it contributes to the backbone of this bar. Maciejewski & Sparke constructed a potential which admits simultaneously loops following the inner and the outer bar. Regular (though not closed) orbits of particles populating these loops support the potential of their model, making it dynamically possible. This is the standard model of Maciejewski & Sparke.

In order to minimize the number of chaotic zones around resonances, the standard model assumes resonant coupling between the bars: corotation (CR) of the inner bar coincides with the ILR of the outer bar. In this potential, loops originating from the $x_1$ orbits in the large-scale bar (the $x_1$ loops) continue to support that bar, while loops that come from the $x_2$ orbits (orthogonal to the large-scale bar, and extending inwards from its ILR), now diversify. The outer $x_2$ loops remain perpendicular to the outer bar, but the inner ones start to follow the secondary bar in its motion, forming its backbone. Since the dynamics of the outer $x_2$ loops is still dominated by the outer bar, the dynamically possible inner bar cannot extend that far in radius, and should end well inside the ILR of the outer bar. In resonant coupling, this means that the secondary bar should end well inside its own CR.

Only a bar extending almost to its CR develops straight shocks (Athanas-soula 1992). If the bar is shorter, shocks start to curve and weaken, and eventually disappear into a ring around the bar. Because the inner bar in the standard model extends only to about half of its CR radius, it may lack principal shocks or dust lanes. In addition, loops that support it originate from the $x_2$ orbits in the outer bar: they are rather round, with no cusps, so there is no reason for shocks in the gas flow to develop. Recently, Maciejewski et al. (2002) modeled hydrodynamically gas inflow in the standard model, and confirmed predictions from the orbital analysis: in their models no stationary straight shocks develop in the secondary bar, but the flow organizes into various elliptical and circular rings.

3. Proposed alterations to the standard model

In the standard model, the inner bar does not extend to its CR radius, and therefore the gas flow that it induces is completely different from that in the outer bar. Two assumptions of the standard model may influence this result. First, this model was constructed to explore possibly biggest secondary bars, and has a large radius of outer bar’s ILR (38% of its CR radius). Secondly, the resonant coupling was assumed. Below, I examine what happens when these two assumptions are lifted.
Figure 1. Two alternative setups of nested bars outlined by solid ellipses. CR of the inner bar (CR$_S$), and ILR of the outer bar (ILR$_B$) are marked with dashed circles. Left: bars in resonant coupling with the inner bar ending well inside its own CR. Right: no resonant coupling between the bars — each bar can extend to its own CR, generating inflow in its own pair of shocks.

**Resonant coupling with smaller ILR radius:** The ILR can be moved to arbitrarily small radii by decreasing the extent of the central mass concentration. For example, a power-law rotation curve $\Omega = ar^{-b}$ implies the ratio of the ILR and CR radii to be $(1 - \sqrt{1 - (b/2)})^{1/b}$, which can be arbitrarily small for $b \to 0$ (i.e. when approaching solid body rotation). Now, consider a large-scale bar extending almost to its CR, and the inner bar ending at about the ILR of that large-scale bar. If the ILR/CR ratio is small, potential of the inner bar should dominate the region inside the ILR, and the inner bar should be able to drag all the $x_2$ loops. In this case, a doubly barred system in resonant coupling with both bars extending to their respective CRs would be possible.

Although only loop calculations can verify plausibility of this model, its setup is unrealistic if the secondary bar forms from the instability in the nuclear disk in the outer bar. Simulations of gas flow in a single bar show that the nuclear ring or disk forms when the ILR is present, with a family of $x_2$ orbits inside it. Gas moving into these $x_2$ orbits is responsible for the offset of the straight shocks from the bar’s major axis already inside the ILR, and outside of the nuclear ring (disk, spiral), on which gas eventually settles. Thus the outer radius of the nuclear disk is always considerably smaller than the ILR radius. If the inner bar forms from this nuclear disk, there is no disk material to extend the inner bar to its CR, which for resonant coupling is at the outer bar’s ILR. This reaffirms findings of the standard model: the inner bar cannot extend to its own CR in doubly barred galaxies with resonant coupling. Accordingly, resonant coupling excludes straight shocks in the inner bar, implying that such double bars do not increase gas inflow like the large-scale bars do. The left panel of Figure 1 illustrates this situation.

**No standard resonant coupling:** An alternative to the standard model is shown in the right panel of Figure 1, where the standard resonant coupling between the bars has been lifted. In principle, the secondary bar in such systems can extend to its CR radius, and it can create shocks in gas flow, which in turn enhance the inflow. However, systems without any resonant coupling are likely to be unstable, because the number of chaotic zones doubles there.
One can consider a different resonant coupling when the $\Omega - \kappa/2$ curve has a local maximum, outside of which it drops to zero at very small and large radii. In this case, the line of constant bar pattern speed intersects this curve twice, and two ILRs form. The standard case was assuming resonant coupling between the outer ILR of the large bar and the CR of the small bar. Now, consider coupling between the inner ILR of the large bar and the small bar’s CR. The dynamics of such a system drastically differs from the standard model, because inside the inner ILR there are no $x_2$ orbits, from which the loops supporting the inner bar used to originate. Detailed loop calculations may find how such systems support themselves, but there are no clear candidates that can naturally follow the secondary bar. In addition, some inner ILRs observed at the small bar’s end can be artificial effects of data resolution: seeing or beam smearing makes inner velocity growth look linear, which falsely implies an inner ILR. The lack of an inner ILR can in fact be beneficial for the inner bar, because in this case the $x_2$ loops that support it may extend all the way to the galactic centre.

4. Conclusions

By constructing a dynamically possible doubly barred galaxy, Maciejewski & Sparke (2000) showed that double bars, just like single bars, can be supported by regular orbits. However, unlike single bars, their inner bar does not extend to its CR radius, and therefore it neither creates shocks in gas flow, nor increases the inflow. The loop approach was necessary in reaching this conclusion, because it allows to determine the dynamics of the interface between bars.

Contrary to the standard model of Maciejewski & Sparke, a wide-spread conviction persists that nested bars should increase gas inflow. Here, I attempted to waive two most vulnerable assumptions of the standard model in order to find candidates of dynamical systems, in which the secondary bar could extend to its CR, therefore being able to enhance the inflow. I found that making the ILR radius of the large-scale bar smaller can lead to a self-consistent model of a doubly barred galaxy in resonant coupling with both bars extending to their CRs, but such a model is unrealistic if the secondary bar forms from the instability in the nuclear disk. Both bars extending to their CRs may occur in systems without any resonant coupling, but such systems may prove chaotic. One should expect completely different dynamics when the CR of the small bar couples with the inner ILR of the large bar.

References

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