 Bars within Bars in Galaxies

Witold Maciejewski and Linda S. Sparke

Department of Astronomy, University of Wisconsin, 475 N. Charter St., Madison, WI 53706-1582

Abstract. Inner regions of barred disk galaxies often include asymmetrical, small-scale central features, some of which are best described as secondary bars. Because orbital timescales in the galaxy center are short, secondary bars are likely to be dynamically decoupled from the main kiloparsec-scale bars. We found that non-chaotic multiply-periodic particle orbits can exist in potentials with two dynamically decoupled bars. Stars trapped around these orbits could form the building blocks for a long-lived, doubly-barred galaxy. A self-consistent secondary bar appears to induce formation of inner gaseous rings rather than shocks in gas flow.

1. Basic concepts

A number of nearby barred galaxies shows isophotal twists within the central few hundred parsecs: the signature of a secondary bar (Erwin & Sparke 1998, this volume). The inner bars appear to be oriented randomly with respect to the larger bars (see e.g. Friedli 1996), as expected if they are dynamically distinct subsystems. Their presence in infrared images suggests they may contain old stars, and do not consist purely of young stars and gas.

Understanding the dynamical state of these inner bars — whether they are long-lived or transient, and what orbits the stars and gas follow within them — requires knowledge not only of the size, shape and strength of the bar, but also of whether its orientation is fixed with respect to the main bar, or rotates about the galaxy center with some nonzero pattern speed. Within about 100 pc of a galactic center, orbital times are at least an order of magnitude less than those at a few kiloparsecs, thus a dynamically decoupled inner bar is likely to rotate faster than the outer structure. The entire pattern is then not steady in any reference frame. Orbits in the doubly barred potential do not have a conserved integral of motion, and in principle they might all be chaotic, exploring large regions of phase space. If the orbits are mostly chaotic, it is unlikely that such a system could be self-consistent, so that the average density of all the stars on their orbits in the time-varying potential adds up exactly to give rise to the potential in which they move. Nevertheless, secondary nuclear bars have been

1 also Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany, witold@mpia-hd.mpg.de
seen to form in numerical simulations involving gravitating particles together with dissipative ‘gas clouds’ (see e.g. Friedli 1996).

How can potentials including two independently rotating bars maintain themselves as gravitating systems? What are the conditions under which a gravitationally self-consistent double-bar structure could exist? We approach these questions by considering models that include two rigid bars, which rotate at two constant, incommensurable pattern speeds, with other galaxy model components defined after Athanassoula (1992). Among these, we look for models that are close to being self-consistent, i.e. those supporting orbital families capable of hosting sets of particles that together recreate the assumed time-dependent density distribution. In the stationary potential of a single bar, particles on a closed periodic orbit move along it, always staying on the same curve, which is the orbit — the backbone of a steady potential. Orbits in a double-barred galaxy will generally not be closed in any uniformly rotating frame of reference, since particles there undergo two forcing actions with non-commensurable frequencies.

We want to extend the definition of an orbit, in order to find closed curves which can serve as backbones of a non-steady, doubly barred system. We search for curves that return to their original positions every time the bars come back to the same relative orientation. We call these curves the loops: a particle that begins its orbit from a position along a given loop returns to another point on the same loop after the bars have realigned. Loops change their shape as the bars rotate through each other. Particles trapped around loops that stay aligned with the bars in their motion could form the building blocks for a long-lived, self-consistent, doubly-barred galaxy. In general, every time the bars realign, the particle takes a different position on the loop; eventually it fills the whole loop. Thus we only need to know the initial conditions for one particle to recover the whole loop. The initial guess can be taken from the epicyclic approximation, in which the loop is a set of particles with the same guiding radius (Maciejewski & Sparke 1997).

2. Loops supporting a doubly barred galaxy

In our models, the most important loop families occupy the same parts of phase space as the $x_1$ and $x_2$ orbits in the single bar. The loop family corresponding to the $x_1$ orbital family in the main bar (the $x_1$ loops) often breaks into an inner part $x_{1i}$ and an outer one $x_{1o}$; there appear to be no stable loops at intermediate radii. In Figure 1, loops belonging to the $x_{1o}$ family are elongated vertically, and located outside a loop that intersects itself at bars aligned (the upper-left panel). The $x_{1i}$ loops, for clarity displayed on the inner panels only, reside inside the secondary bar and also remain vertical. The loop family that at large radii corresponds to the $x_2$ orbital family of the main bar changes continuously with decreasing radius; it begins to follow the secondary bar in its motion, so it eventually corresponds to its $x_1$ orbital family. We will call this family the $x_2$ loop family: like the $x_2$ orbits in a single bar, these loops do not extend all the way to the center. This family is represented by a set of horizontal loops on the lower-right panel of Figure 1, and by corresponding sets on other panels. No loop family corresponding to the $x_2$ orbital family in the secondary bar has been found.
Figure 1. Loops in a doubly barred galaxy, at different relative positions of the bars, displayed in the reference frame of the main bar, which remains vertical. The outer bar is outlined in dashed and the major axis of the secondary bar is marked by a straight line. The sequence follows along outer panels clockwise, with central regions magnified on inner panels, where the secondary bar is outlined in dashed. Units on the axes are in kiloparsec.
The loops supporting the secondary bar are those $x_2$ loops which rotate smoothly with its figure. They change axial ratio as the bars rotate, and lead or trail the figure of the secondary bar: a self-consistent secondary bar is likely to pulsate and accelerate as it revolves inside the main bar. We find that the size of a self-consistent secondary bar is approximately limited by the maximum extent of the $x_2$ orbits along the main bar’s major axis. Since a strong secondary bar can easily disrupt orbits supporting the main bar, its mass is limited by the requirement that a substantial part of the main bar is supported by the $x_1$ loops, so that the galaxy remains doubly barred. Even then, the $x_{1o}$ loops are strongly influenced by the motion of the secondary bar (they get rounder when the bars are orthogonal), and we were not able to find any $x_1$ loops supporting the inner part of the main bar when the secondary bar is perpendicular to it. A partial support to the inner region of the large bar is given by another loop family (we call it the $b_T$ family), represented in Figure 1 by the curve which intersects itself at bars aligned (upper-left panel), and remains aligned with the main bar.

3. Gas flows in doubly barred galaxies

We model the flow of isothermal gas using the CMHOG PPM code (written by James M. Stone, modified by Piner et al. 1995) on a staggered grid in planar polar coordinates ($\Delta R\simeq R\Delta \varphi$), which gives excellent resolution of circumnuclear phenomena near the grid center. Initially, uniformly distributed gas is in circular motion; the potential of the primary bar is then smoothly imposed. The secondary bar is introduced after the flow in a single bar has been stabilized.

The interior of the nuclear ring, formed by gas flow in a single bar (see Piner et al. 1995), assumes an elliptical shape in the presence of a secondary bar. The interior begins to rotate with the secondary bar, and eventually an elliptical ring forms around it. A circular disk develops inside the ring; this disk turns into another, circular ring by the end of the simulation. Neither of the rings forms a shock — the gas moves along the rings, and inside the inner circular ring it is in almost perfect circular motion. The lack of shocks within the secondary bar (unlike in the primary bar, where they manifest themselves as dust lanes) can be explained by recalling, that because of the limitations imposed by the orbital structure, this bar extends only about half-way to its corotation. Athanassoula (1992) found that in this case the dust lanes curl around the bar and start forming a ring. Therefore some self-consistent doubly barred galaxies may lack secondary shocks or dust lanes, and may not induce strong gas inflow to the galaxy center. A better exploration of possible potentials is needed in order to reach firmer conclusions.

References

Athanassoula, E. 1992 MNRAS 259, 345
Friedli, D. 1996 in ‘Barred Galaxies’, IAU Colloq 157, eds. R. Buta et al. ASP Conf. Ser., p378
Maciejewski, W. & Sparke, L.S. 1997 ApJ 484, L117
Piner, B.G., Stone, J.M. & Teuben, P.J. 1995 ApJ 449, 508