ON THE NATURE OF INNER RINGS IN BARRED GALAXIES*

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Abstract: Inner rings in barred spiral galaxies are associated with specific 2D and 3D families of periodic orbits, which are found in the upper part of a type-2 gap of the x1 characteristic. Using these orbits we reproduce the observed morphologies of inner rings and we explain why some of them are observed more frequently than others.

1 Introduction

Inner rings are ring-like structures, which surround the bars of barred spiral galaxies. Most inner rings are oval, sometimes with a somewhat lemon shape because of density enhancements at the bar major axis. As a typical case we mention NGC 6782. Some ovals have characteristic breaks or corners. In this latter case the ring becomes rather polygonal-like with sides roughly parallel to the bar's minor axis at its apocentra, and 'corners' close to the minor axis. This morphology is nicely demonstrated by the distribution of the HII regions in IC 4290 (Buta et al. 1998). In exceptional cases we encounter rings that are better described as pentagonal structures, while there is a single notable case, NGC 7020, with an inner hexagonal ring with cusps on the major axis of the bar and two sides parallel to it (Buta 1990).
We use a 3D Ferrers bar model to study the orbital structure of the rings. The model is described as "the fiducial case" in Skokos et al. 2002.
It consists of a Miyamoto disk, a Plummer bulge and a Ferrers bar. The potential of the Miyamoto disk (Miyamoto & Nagai 1975) is given by the formula:

$$\Phi_D = -\frac{GM_D}{\sqrt{x^2+y^2+(A+\sqrt{B^2+z^2})^2}}, \tag{1}$$

where M_D is the total mass of the disk, G is the gravitational constant, and the ratio B/A gives a measure of the flatness of the model.
The bulge is represented by a Plummer sphere, i.e. its potential is given by:

$$\Phi_S = -\frac{GM_S}{\sqrt{x^2+y^2+z^2+\varepsilon_s^2}}, \tag{2}$$

where ε_s is the bulge scale length and M_S is its total mass.

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Finally, the bar is a triaxial Ferrers bar with density $\rho(x)$:

$$\rho(m) = \begin{cases} \dfrac{105M_B}{32\pi abc}(1-m^2)^2 & for \quad m \leq 1 \\ \\ 0 & for \quad m > 1 \end{cases}, \tag{3}$$

where

$$m^2 = \frac{y^2}{a^2} + \frac{x^2}{b^2} + \frac{z^2}{c^2}, \; a > b > c. \tag{4}$$

In the above a, b, c are the principal semi-axes, and M_B is the mass of the bar component. For the Miyamoto disk we use A=3 and B=1, and for the axes of the Ferrers bar we set a:b:c = 6:1.5:0.6. The masses of the three components satisfy $G(M_D + M_S + M_B) = 1$. We have $GM_D = 0.82$, $GM_S = 0.08$, $GM_B = 0.10$ and $\varepsilon_s = 0.4$.
The length unit is taken as 1 kpc, the time unit as 1 Myr and the mass unit as $2 \times 10^{11} M_{\odot}$. The bar rotates with a pattern speed Ω_b=0.054 around the z-axis, which corresponds to 54 km $\sec^{-1}$ kpc^{-1}, and places corotation at 6.13 kpc.
The Hamiltonian governing the motion of a test-particle in our rotating with Ω_b system can be written in the form:

$$H = \frac{1}{2}(p_x^2 + p_y^2 + p_z^2) + V(x,y,z) - \Omega_b(xp_y - yp_x), \tag{5}$$

where p_x, p_y, and p_z are the canonically conjugate momenta of x, y and z respectively and $V(x,y,z)$ is the total potential of the combined three components of the model: disk, bar and bulge.

2 Results

In our 3D Ferrers bar model, inner rings are due to orbits belonging to families in the upper part of the type-2 gap at the inner radial 4:1 resonance (Contopoulos & Grosbøl 1989). They are grouped in two orbital trees, which have as mother-families two planar families we call "f" and "s". The orbits that make the rings belong in their vast majority to three-dimensional families of periodic orbits. These 3D families have large stable parts and thus they increase considerably the volume of the phase space occupied by ring-supporting orbits. The energy width over which we can find stable 3D orbits supporting the rings is larger than the corresponding interval of 2D stable families.
The prevailing types of inner rings are variations of oval shapes and are determined by the way the f and s families are introduced in the system. This is the tangent bifurcation mechanism. In such a bifurcation (also known as saddle-node bifurcation) one of the newborn sequences of orbits is unstable (the saddle), while the other is stable (the node) (see Contopoulos 2002, pg. 102). The

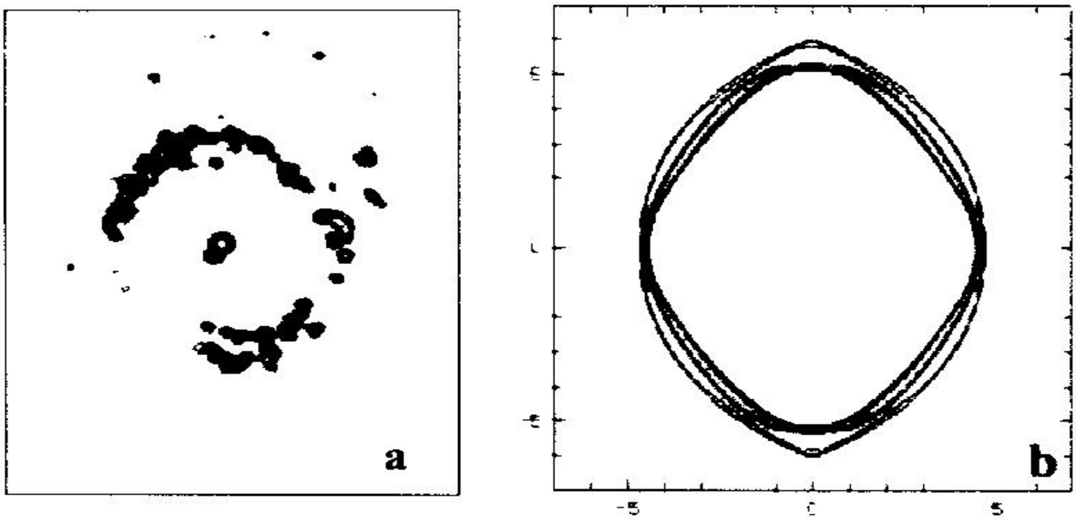

Figure 1: (a) The distribution of HII regions in IC 4290 as given in Buta et al. (1998). (b) The face-on view of a set of stable orbits belonging to the f- and s-trees. The HII regions outline the inner ring structure, and the set of the orbits we present reproduces the observed morphology

characteristics of families f and s are of this type, which means that these families are *not* bifurcated from any family belonging to the the x1-tree (Skokos et al. 2002). Furthermore, they build their own group of families, i.e. their own trees.

The orbits on the stable branch of their characteristic, together with their stable 3D bifurcations, support ovals with a more or less strong lemon shape, or oval-polygonal rings with 'corners' along the minor axis of the bar. These types of inner rings represent frequently observed morphologies.

In Fig. 1 we see at the left panel the distribution of the HII regions in IC 4290 (Buta et al. 1998) and at the right one a combination of weighted (see Patsis et al. 2003) stable orbits belonging to the f- and s-trees of families. These orbits can reproduce the distribution of the HII regions, that outline the shape of the inner ring in this galaxy.

Pentagonal rings are rare because the families building them have small stable parts and usually come in symmetric pairs. These families belong to the f-tree. Thus, in order for these rings to appear, the symmetry must be broken and only one of the two branches be populated due to some particular formation scenario. Furthermore, considerable material should be on regular non-periodic orbits trapped around stable periodic orbits existing only in narrow energy ranges.

If orbits are trapped around stable s periodic orbits at the energy minimum of the s characteristic, then an NGC 7020 morphology can be reproduced. Although such a morphology is in principle possible, it should be rare, because it would necessitate that considerable amount of material be on regular orbits trapped around periodic orbits in a very narrow energy interval. Indeed the hexagonal orbits with cusps on the *major* axis are on the unstable branch of the tangent bifurcation.

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3 References

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