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The face-on views of X-shaped "bulges" - boxy features in the central parts of bars

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Abstract. Boxiness associated with the morphology of the central parts of bars, is a feature usually encountered in the edge-on profiles of galaxies, or galactic models. However, there are cases where "boxy" isophotes are observed also in the central parts of nearly face-on bars. I summarize here some dynamical mechanisms that support boxy orbits in the central bar regions on the equatorial plane of the disks, or orbits with boxy projections on it. Such orbits could describe the dynamics of $face-on$ boxy "bulges".

Keywords. Galaxies: kinematics and dynamics – Galaxies: spiral – Galaxies: structure

1. Introduction

As boxy "bulges" we usually characterize the central regions of disk galaxies observed edge-on, which have a boxy morphology. It is believed that they are rather part of bars (e.g. Athanassoula 2005) than classical bulges. However, there are also many cases, where boxy structures appear embedded in the central regions of barred-spiral galaxies observed nearly face-on. Several examples can be found e.g. in Buta (1995) or in Erwin & Debattista (2013).

The presence of boxy features in the inner regions of face-on bars cannot be attributed to the presence of stable periodic orbits (hereafter p.o.) of rectangular-like morphology on the equatorial plane, since we are away from resonances like the radial 4:1. Stable periodic orbits with boxy shape, such as those found at the 4:1 resonance, could introduce quasi-periodic orbits of similar morphology in the system and thus secure the appearance of rectangular-like features in the region. However, the central parts of a galactic bar are most likely associated with the inner 2:1 resonance, a region where the elliptical-like x1, and x2, p.o. dominate in phase space. In addition, the projections on the equatorial plane of the two main, "three-dimensional" (3D), x1 bifurcations at the vertical 2:1 resonance region (in general being very close also to the radial 2:1 region) are again elliptical-like. So, it is expected to face the same problem in supporting boxy features via the orbital trapping mechanism.

Possible dynamical mechanisms that could lead to rectangular-like motions of stars in the inner regions of bars on the equatorial plane, or to boxy projections of orbits on this plane, have been proposed in the last years in a series of papers (Katsanikas *et al.* 2013 (KPC), Patsis & Katsanikas 2014a (PKa), Patsis & Katsanikas 2014b (PKb), Tsigaridi & Patsis 2013 (TPa), Tsigaridi & Patsis 2015 (TPb), Chaves-Velasquez *et al.* 2017 (CPPSM), Patsis & Harsoula 2018 (PH), Patsis & Athanassoula 2019 (PA)). Here, I summarize the results of these studies.

2. Modelling

In all the papers mentioned in the last paragraph of the introduction, modelling is based on autonomous Hamiltonian systems of rotating potentials. The equations of motion are derived from Hamiltonians of the form (in Cartesian coordinates):

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

where x, y, z are the spatial coordinates, p_x, p_y, and p_z are the canonically conjugate momenta, Φ is the potential and Ω_p is the angular velocity of the system (pattern speed). The numerical value of the Hamiltonian, is the conserved Jacobi constant.

In most studies (PKa, PKb, CPPSM, PA) the bar potential is expressed with a Ferrers bar (combined with different axisymmetric backgrounds), in PH it corresponds to the potential of an N-body's simulation snapshot, in KPC the potential consists of two perturbed Miyamoto disks, while in TPa and TPb a two-dimensional (2D) formalism with a potential estimated from near-infrared observations of a galaxy has been considered.

3. Results

• The orbital content of rotating, 3D bars that are modelled as autonomous Hamiltonian systems is generic. The shape of the orbits is determined by the presence of the resonances. Thus, the same orbital families are found in all models we used, as well as in other cases, in which no explicit bar component is included (see e.g. Patsis & Grosbøl 1996, Chaves-Velasquez *et al.* 2019). The relative significance of each family though, varies from model to model.

• Elliptical-like morphologies in the central parts of face-on bars, can be supported by regular orbits trapped on tori in the *immediate neighbourhood* around x1 and on tori around its stable 3D bifurcation at the vertical 2:1 resonance region. Sticky chaotic orbits associated with the unstable 3D bifurcation of x1 at the same resonance, can also have elliptical projections on the equatorial plane.

• Moving on the surfaces of section from the center of the stability islands of the planar x1 orbits towards the borders of these islands, we encounter, as expected, zones that consist of chains of smaller stability islands with filamentary, chaotic regions between them. They reflect the presence of successive stable and unstable p.o. of multiplicity higher than one, that appear in pairs, symmetric to each other (see e.g. figure 2.58 in Contopoulos 2004). In these zones, due to the symmetry of the orbits, boxy orbital structures are formed on the equatorial plane. Boxy orbits on the equatorial plane can be also found in the sticky chaotic regions at the borders of the stability islands.

• In general, orbits that support inner boxy structures in the face-on views of 3D bars have two main origins:

(a) Orbits that are found by perturbing vertically the boxy orbital structures on the equatorial plane. There are ranges of vertical perturbations for which the projections of these 3D orbits on the equatorial plane are boxy.

(b) Chaotic orbits, sticky (Contopoulos & Harsoula 2013) to the stable 3D bifurcations of x1 at the vertical 2:1 resonance (usually the x1v1 and x1v1′ families, following the nomenclature of Skokos *et al.* 2002). These sticky-chaotic orbits may have x1v1-like, or x1v2-like (Skokos *et al.* 2002), or hybrid, side-on morphologies. The projections of such orbits on the equatorial plane, reinforce boxiness in the central parts of bars.

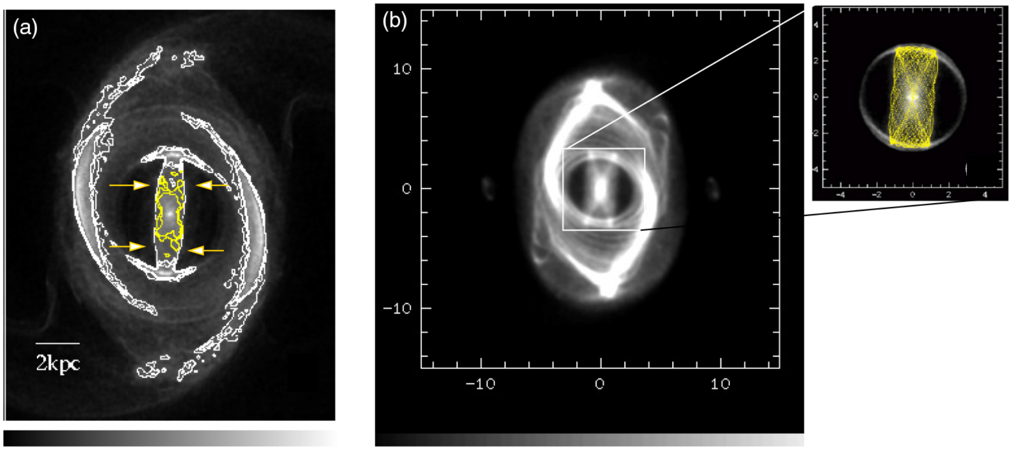

Figure 1. Two snapshots of response models with the 2D barred-spiral potential presented in TPa and TPb. In (a) the ratio of the corotation to bar radius is 2.9, while in (b) it is 3.5. The bar in (a) has a central boxy region that extends to half the distance to the end of the bar and it is highlighted with a yellow isodensity. An X feature is embedded in it and its extremities are indicated with four arrows. In (b) the boxy region is the bar itself and the X is clearly discernible, reinforced by orbits like the one given overplotted to the model in enlargement, in the frame at the upper right side of (b).

• The rectangular-like projections of sticky chaotic orbits on the equatorial plane in some cases support even X-features *in the face-on views* of the bars. We find that these *face-on X-features* are more pronounced in slow pattern speed models.

• Following a 2D formalism to study the problem, we reached the same conclusions as regards the role of sticky chaotic orbits around the stability islands of x1, in supporting boxy structures harbouring X features in them (TPa, TPb). Also in this case we find that the boxy morphology occupies a larger fraction of the bar, and the X-feature is more evident, in slow rotating systems (Fig. 1). The presence of *face-on* X's, embedded in boxy "bulges", and the reinforcement of rather circular rings surrounding the bars, reproduce a morphology resembling that of galaxies like IC 4290 or IC 5240 (see e.g. Buta 1995).

4. Conclusions

Our results strongly indicate that boxiness in the face-on morphology of barred galaxies is favoured by the presence of weakly chaotic and sticky chaotic orbits in the system. On the equatorial plane of the models, orbits in zones with small stability islands and chaotic layers between them, on the x1 stability islands, as well as sticky chaotic orbits, support boxiness. Although this is a main dynamical mechanism that leads to the formation of inner boxy structures, it applies everywhere on the bars and not only in the 2:1 resonance region. However, in the thick part of the bars, where the peanut-shaped "bulges" are observed in the edge-on views of the models, the role of chaotic orbits, sticky to 3D bifurcations of x1, is also important for the appearance of boxy "bulges" in the face-on views. Such orbits can give rectangular-like projections on the equatorial plane. The other source of orbits with boxy projections on the plane, is provided by vertically perturbed 2D boxy orbits.

Finally, we have to note that boxy edge-on orbital shapes can be combined either with elliptical-like or with rectangular-like face-on morphologies. In the latter case, "double-boxy" orbits may retain in their side-on views, the known shapes of the 3D vertical

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bifurcations of x1 that support the peanut (x1v1 and x1v2 families). Examples of "double-boxy" orbits can be found in CPPSM and PA.

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