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Dynamical mechanisms supporting barred-spiral structures

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We review some recent results of the orbital theory, related with the dynamics of *barred-spiral* galaxies. The method we use is to study the responses of stellar and gaseous disks when time-independent, external potentials are imposed. These potentials are directly estimated from near-infrared images of disk galaxies. The goal of the work is to detect dynamical mechanisms that reinforce the bars and the spirals in realistic systems. Besides the known mechanism for building bars by quasiperiodic orbits trapped around stable orbits of the x_1 family, we find cases where bars can be supported, to a large extent, by chaotic orbits. These bars are of the "ansae" type and their effective potentials are characterized by multiple Lagrangian points roughly along the major axis of the bar. On the other hand the spirals are supported mainly by chaotic orbits and extend usually beyond corotation. We find that the spirals and the outer parts of the bars share the same orbital content. However, we have found also barred-spiral systems with spirals inside corotation, consisting mainly by chaotic orbits. Finally we indicate, that in barred-spiral systems with different pattern speeds for the two components, the dynamics of the spirals can be similar to the dynamics of the spirals of *normal* spiral galaxies.

Keywords: Spiral galaxies; Barred galaxies; Galactic dynamics; Galactic morphology; Stellar orbits

1 Introduction

A basic result of the orbital theory related with the dynamics of galactic bars, is that the orbital backbone of the bars is the x_1 family of periodic orbits [1]. The x_1 family is stable over long intervals of the Jacobi constant (E_J) and traps around it a large number of quasiperiodic orbits. It builds the bar, since the shape of its members is elliptical with apocentra roughly aligned along an axis. Contopoulos [1] also provided evidence that, due to the topology of the x_1 orbits, bars cannot exceed in length the corotation distance. The role of the x_1 family and the corotation limit for the length of the bar summarize the state of the art of our knowledge about the dynamics of galactic bars.

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A main morphological feature of barred-spiral galaxies, that has to be reproduced by models, is that in most systems the spirals appear connected to the bars. In many cases they emerge out of its ends. In systems with a single pattern speed a model has to predict the continuation of the spirals beyond the ends of the bar, through the corotation region, without any discontinuity. Corotation in barred-spiral system is close to the end of the bar, at distances where the strength of the $m = 2$ component of the observed surface brightness is considerably strong if Fourier analyzed (see e.g. [2]). A first attempt to model barred-spiral galaxies by means of the orbital theory by [3] underlined for the first time the necessity to invoke chaotic orbits for building the part of the spirals that is closest to the bar. Also the study by [4] has shown that the characteristic outer boxy isophotes of the nearly face-on bar of NGC 4314 are due to chaotic orbits. These were indications that structure could, under certain circumstances, survive in chaotic zones, such as the corotation region in galactic disks.

Recently the role of chaotic orbits in supporting the spiral structure at the corotation region of barred-spiral galaxies has been studied by several authors (see [5, 6, 10, 12, 15–19] and references therein). There is a general consensus that at least part of the spirals are reinforced by stars in chaotic motion. Reviews of the research of the main groups that work on the subject can be found in [8]. We will refer to this kind of spirals as "chaotic" spirals.

Here we present orbital models that describe successfully the dynamics of the grand design barred-spiral galaxies NGC 4314, NGC 1300 and NGC 3359. The potentials we use have been estimated directly from near-infrared observations of these galaxies.

2 The method

In general the potentials of disks estimated from near-infrared observations, are written in the form

$$\Phi(R,\theta) = \Phi_0(R) + \sum_{k}^{k_{max}} \left[\Phi_{kc}(R)\cos(k\theta) + \Phi_{ks}(R)\sin(k\theta)\right]. \qquad (1)$$

The range of k values in the sum is taken according to the needs of every particular model. Also the amplitudes of the trigonometric terms are discussed separately in each individual case. Additional potential terms for a bulge and a dark matter component are included in the models for NGC 1300. They are omitted in the models for NGC 4314 and NGC 3359, without affecting essentially the dynamics of the outer regions of the bar and the spirals, which we study in the present paper.

We work under the assumption, that, at least during the time we follow the response, the potential can be considered as time-independent, and that the bar and the spirals rotate with the same pattern speed. Equations of motion are derived from the Hamiltonian

$$H \equiv \frac{1}{2}\left(\dot{x}^2 + \dot{y}^2\right) + \Phi(x,y) - \frac{1}{2}\Omega_p^2(x^2+y^2) = E_J, \qquad (2)$$

where (x, y) are the coordinates in the Cartesian frame of reference, rotating with angular velocity Ω_p. $\Phi(x, y)$ is the potential in Cartesian coordinates. E_J is the numerical value of the Jacobi constant and dots denote time derivatives.

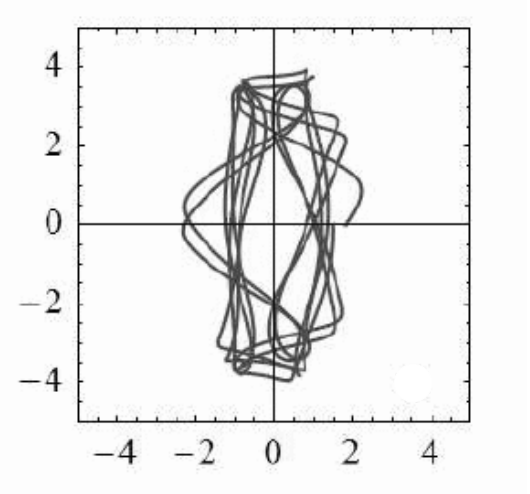


Figure 1 A characteristic chaotic orbit in the [14] potential. These orbits shape the outer envelope of the bar and give to it its rectangular-like morphology.

For the response models, we populate initially a disk within a R_{max} radius by placing 10^5 to 10^6 test particles at random positions and in circular motion in the axisymmetric part of the potential $\Phi_0(R)$. We grow the non-axisymmetric terms of the potential linearly from 0 to their final value within two pattern rotations. We integrate the particles' orbits for 10 pattern rotations. By continuing the integration of the orbits for more pattern rotations, we do not observe essentially any change in the morphology of the snapshots. Finally we construct density maps, by converting our data files to images using the ESO-MIDAS software. For this we consider a grid and we take into account the numerical density of the test particles on the disk.

3 Bars partly supported by chaotic orbits

Patsis et al. [4] have indicated that the outer envelope of the bar of NGC4314 is built by chaotic orbits. The potential used has been estimated by [14] and is of the form of Eq. 1 with $k = 2, 4, 6$. The reader may refer to [14] for details of the potential. In the study by [4] it has been used for the pattern speed $\Omega_p = 44.96$ km s^{-1} kpc^{-1}. Patsis [10] found that for $38.23 < \Omega_p < 46$ km s^{-1} kpc^{-1} we have for this potential qualitatively the same dynamics that determine the morphology of the model, being in good agreement with the NGC 4314 structure. A typical chaotic orbit that contributes to the characteristic boxy morphology of the NGC 4314 is given in Fig. 1.

Another case, where we have found an even larger contribution of chaotic orbits to the reinforcement of a bar structure, has been studied by [12]. In a potential estimated from K-band observations of NGC 1300, it has been realized that in a range of pattern speeds $19 < \Omega_p < 24$ km s^{-1} kpc^{-1}, the response bars have been supported mainly by particles in chaotic motion. The potential of the disk is also of the form of Eq. 1,

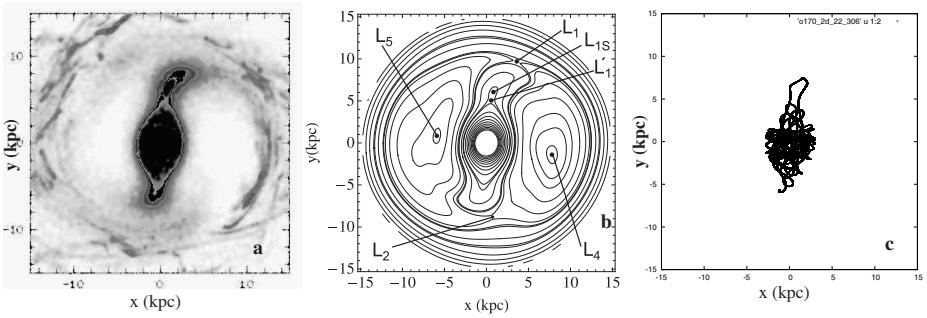


Figure 2 "Ansae"-type bars can be formed mainly by chaotic orbits. (a) A response model of the NGC 1300 potential with Ω_p=23 km s^{-1} kpc^{-1} [9]. (b) Isocontours of the effective potential for Ω_p=22 km s^{-1} kpc^{-1} , where the multiple Lagrangian points are indicated with arrows. (c) A typical chaotic orbit, which supports the bar.

with odd terms included as well ($k = 1, \ldots 6$). It is described in detail as the 2D case "Model A" in [9], and includes besides the disk, explicit bulge and dark matter halo components.

For the above mentioned range of pattern speeds the response bars have a conspicuous "ansae" type morphology. This morphology can be seen in Fig. 2a for Ω_p = 23 km s^{-1} kpc^{-1}. The bars become thicker, and the "ansae" morphology less pronounced, as the pattern speed decreases. These models are characterized by multiple stable and unstable Lagrangian points. Close to the major axis of the bar we have four Lagrangian points, three of which are unstable (L_1, L_1', L_2) and one stable L_{1S}. They are indicated with arrows in Fig. 2b, which describes the landscape of the effective potential for Ω_p = 22 km s^{-1} kpc^{-1}. Stable x_1 orbits can build only the central part of the bar ($R < L_1'$) by quasiperiodic orbits trapped around them. Beyond this region, the particles in the bar have E$_J$'s, for which not only the $x_1$orbits, but almost all periodic orbits are unstable and in the surfaces of sections chaos dominates [12]. However, the structure of the bar survives in these chaotic regions, being built by chaotic orbits. A typical example of such an orbit is given in Fig. 2c. The mechanism is based on the presence of multiple Lagrangian points roughly along the major axis of the bar. Multiple Lagrangian points are necessary in order to build the appropriate shapes of the isocontours in the effective potential.

4 "Chaotic" spirals

In order to study the orbits that reinforce the response spirals we first isolate the particles located on them and then we perform statistics of their Jacobi constants (E$_J$) [10, 12]. So, we find out that the vast majority of these particles have E$_J$'s, close to the value of E$_J$ at corotation (E$_{L_{1,2}}$), where chaos dominates on the surfaces of section. We have found two mechanisms building "chaotic spirals".

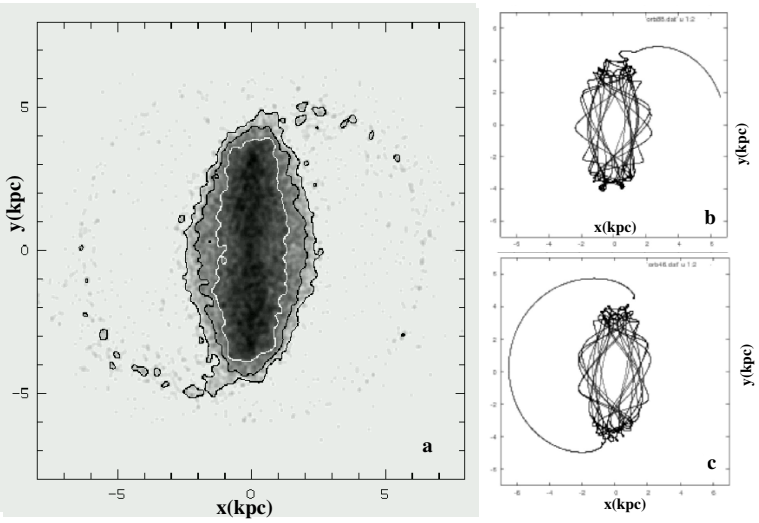


Figure 3 (a): A response model in the [14] potential, rotating with Ω_p = 38.23 km s^{-1} kpc^{-1}. (b) and (c): Typical chaotic orbits visiting both the bar and spiral regions. They have a 4:1 resonance character inside corotation. The superposition of many such orbits reinforce the spirals.

4.1 Beyond corotation

The response models of the [14] potential, as well as the "ansae" type response bars in the NGC 1300 potential, are accompanied by "chaotic" spirals. The particles on them belong to a hot orbital population [13] that visits both the bar and the disk. The spirals are formed by a mechanism involving the unstable manifolds of unstable periodic orbits [5, 10, 15–19]. In our models, at the E_J 's of the particles on the spirals we find members of the unstable families around L_1 and L_2, as well as of the 4:1 resonance family. The stellar spirals formed this way fade out at an angle about $\pi/2$ away of the bar's ends. In Fig. 3a we observe the response bar in the [14] potential with Ω_p = 38.23 km s^{-1} kpc^{-1}, together with two characteristic chaotic orbits (Fig. 3b,c), which extend also along the spirals. The spirals are supported by many orbits like these in Fig. 3b,c, which follow similar paths when they leave the bar region. We can see that these orbits visit the bar and the area of the spirals. They have morphologically a strong 4:1 resonance character in their parts inside corotation. The mode of the statistics of the E_J for the particles on the spirals is inside an interval that includes both the Jacobi constant $E_{L_{1,2}}$ of the unstable Lagrangian points L_1, L_2 and the E_J 's at which there is a rectangular 4:1 resonance family in the system [7].

A similar mechanism forms the spirals in the NGC 1300 models with the ansae bars. In Fig. 4a we give the response model for Ω_p=22 km s^{-1} kpc^{-1}, and in Fig. 4b a typical chaotic orbit that supports both the "ansae" character of the bar and the spirals [12]. In the NGC 1300 models, by decreasing Ω_p, the bar becomes thicker, the ansae less conspicuous and the "chaotic" spirals beyond corotation more pronounced.

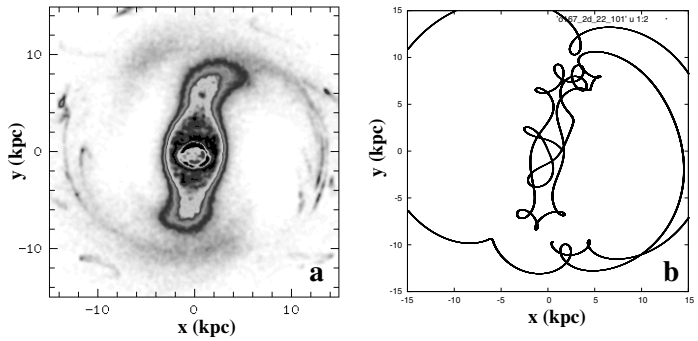


Figure 4 (a): A response model with an "ansae" bar in the NGC 1300 potential, with "chaotic" spirals beyond corotation. (b): A typical chaotic orbit supporting the spirals.

4.2 Inside corotation

In the same potential for NGC 1300 as in the previous case, but for $\Omega_p = 16$ km s^{-1} kpc^{-1} we find spirals formed again by chaotic orbits. However, this time the spirals are inside corotation. In the effective potential (Fig. 5a) the region inside corotation is separated from the region outside corotation by the isocontour drawn with a thick line and is indicated with a thick arrow (upper part of the figure). In Fig. 5b we give the density map of the response model. The chaotic orbits of the particles on the spirals are in this case mainly of the kind we observe in Fig. 5c. This means, that the local density maxima of the rsponse model on the spirals occur as the particles perform a motion like "bouncing" on the heavy isocontour of Fig. 5a. In Fig. 5c the orbit has been plotted over a density map of the model, in which denser areas are colored with darker shades. The perimeter of the grey region on which the orbit is "bouncing", practically coincides with the heavy isocontour of the effective potential in Fig. 5a. We have to note that the spiral arms formed with this mechanism in the model rotating with Ω_p=16 km s^{-1} kpc^{-1} that we study here, represent best the spiral arms of NGC 1300, than any other of the models in [12].

5 Barred-spiral systems behaving like normal spirals

As a last case we mention the model found to match the observational features of NGC 3359, studied by [11] by means of stellar and gaseous response models. Given that the pattern speed in a galaxy is unique for the stellar and gas components, the dynamics of a gas model has to result to a morphology for the young objects on the disk compatible with the corresponding stellar image. We found, that the spiral dynamics in this case is similar to those for normal spiral galaxies. Features as the alignment of the HII regions along the spirals (Fig. 6) can be reproduced only by assuming a corotation of the spirals close to their ends. Thus, the spiral arms extend inside corotation. In this case we can find a backbone of stable periodic orbits, which

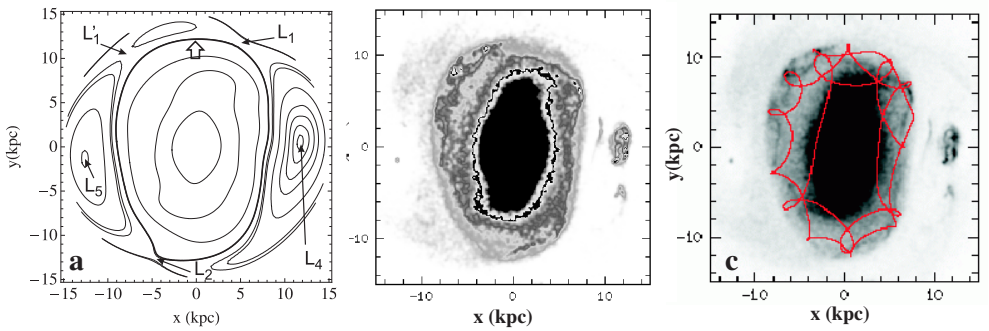


Figure 5 (a): The 2D effective potential ("Model A" in [9]) with Ω_p = 16 km s^{-1} kpc^{-1}. (b): A response model in the NGC 1300 potential, with "chaotic" spirals inside corotation. (c): A typical chaotic orbit supporting the spirals.

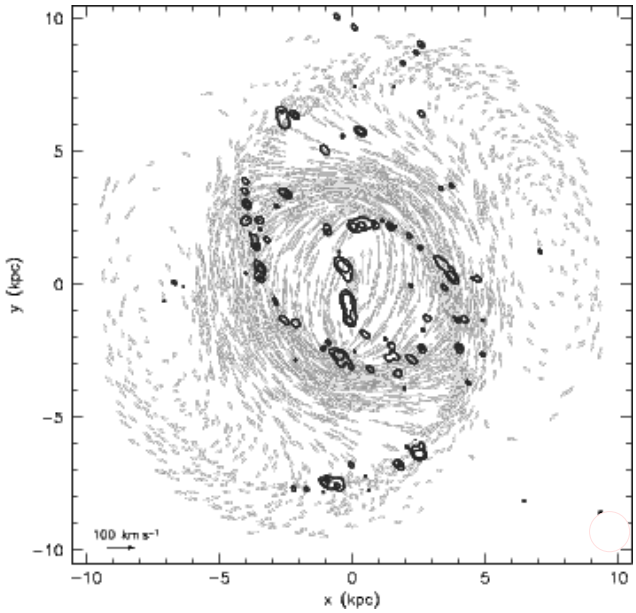


Figure 6 The velocity field of the *gas-response* model for NGC 3359 (grey arrows) having the spiral corotation close to the end of the spiral arms, together with the HII regions of the galaxy (black regions). We observe that their location is in agreement with a "precessing ellipses" flow.

are precessing ellipses, to build the spirals by quasiperiodic orbits trapped around them. In [11] we found, that the best matching model has to adopt different pattern speeds for the bar and the spirals. Then, we have a corotation for the bar close to its end and another corotation for the spirals close to the end of the spiral arms.

6 Discussion and Conclusions

The general conclusion of these and other studies on the subject is that Chaos plays a very important role in shaping barred-spiral galaxies (at least when the two components, bar and spirals, share the same pattern speed). Below we enumerate our main conclusions:

Our results for the bar component are the following:

1. Besides the bars, which have as backbone the stable $x_1$family, in our models we find bars with their outer envelope made out of chaotic orbits. They have a rectangular-like shape as indicated by [4] (Fig. 1).
2. We have found also a case with an ansae-type bar that is built essentially by chaotic orbits (Fig. 2). The mechanism is based on the presence of multiple Lagrangian points roughly along the major axis of the bar. Multiple Lagrangian points are necessary in order to build the appropriate shapes of the isocontours of the effective potential.

As regards the spirals we have found that:

1. In our models for early type *stellar* bars we have spiral arms beyond corotation supported by particles in chaotic orbits. They are formed by the mechanism involving unstable manifolds of unstable periodic orbits at E_J 's, where we find members of the unstable families around L_1 and L_2 as well as the 4:1 resonance family. The spiral supporting orbits in these E_J 's have morphologically a strong 4:1 resonance character in their parts inside corotation. The spirals formed this way fade out at an angle about $\pi/2$ away of the bar's ends (Figs. 3 and 4).
2. We found also spirals supported by chaotic orbits, *inside corotation*, via a dynamical mechanism summarized in Fig. 5. These spirals match the morphology of the spiral arms of NGC 1300.
3. The two pattern speeds case has the corotation of the spiral pattern close to the end of the spirals. The observed spiral morphology is compatible with a "precessing ellipses flow". Both bar and spirals are built by regular orbits. In this case we have a dynamical behavior similar to what we find in *normal* spiral galaxies.

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References

[1] Contopoulos G., 1980, A&A 81, 198
[2] Aguerri J.A.L., Beckman J.E., Prieto M., 1998, AJ 116, 2136
[3] Kaufmann D.E., Contopoulos G., 1996, A&A, 309, 381

[4] Patsis P. A., Athanassoula E., Quillen A. C., 1997, ApJ, 483, 731
[5] Athanassoula E., Romero-Gómez M., Masdemont J. J. 2009, MNRAS 394, 67
[6] Contopoulos G., 2009, in "*Chaos in Astronomy*", G. Contopoulos and P.A. Patsis (eds), Springer-Verlag Berlin Heidelberg, pp. 3-22
[7] Contopoulos G., Grosbøl P. 1989, Astron. Astroph. Rev. 1,261
[8] Contopoulos G., Patsis P.A. (eds), 2009, '*Chaos in Astronomy*", Springer-Verlag Berlin Heidelberg
[9] Kalapotharakos C., Patsis P.A., Grosbøl P. 2010a, MNRAS 403, 83
[10] Patsis P.A., 2006, MNRAS 369L, 56
[11] Patsis P. A., Kaufmann D.E., Gottesman S.T., Boonyasayt V., 2009, MNRAS 394, 142
[12] Patsis P. A., Kalapotharakos C., Grosbøl P., 2010, MNRAS 408, 22
[13] Pfenniger D., Friedli D., 1991, A&A 252, 75
[14] Quillen A.C., Frogel J.A., Gonzalez R.A., 1994, ApJ, 437, 162
[15] Romero-Gómez M., Masdemont J. J., Athanassoula E., García-Gómez C. 2006, A&A 453, 39
[16] Tsoutsis P., Efthymiopoulos C., Voglis N., 2008, MNRAS 387, 1264
[17] Tsoutsis P., Kalapotharakos C., Efthymiopoulos C., Contopoulos G., 2009, A&A 495, 743
[18] Voglis N., Stavropoulos I., 2005, in "*Recent advances in Astronomy and Astrophysics*", N. Solomos (ed), AIP Conference Proceedings, Volume 848, pp. 647-659
[19] Voglis N., Stavropoulos I., Kalapotharakos C., 2006, MNRAS 372, 901