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Ordered and chaotic spirals in disk galaxies

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Abstract. The pattern speeds of spiral galaxies are closely related to the flow of material in their disks. Flows that follow the 'precessing ellipses' paradigm (see e.g., Kalnajs 1973) are likely associated with slowly rotating spirals, which have corotation beyond their end. Such a flow can be secured by material trapped around stable, elliptical, x_1 periodic orbits precessing as their Jacobi constant varies. Contrarily, if part of the spiral arms is located at a corotation region then the spiral structure has to 'survive' in chaotic regions. Barred-spiral systems with a single pattern speed and a bar ending before, but close to, corotation are candidates for having spirals supported by stars in chaotic motion. In this work we review the flows we have found in response models for various types of spiral potentials and indicate the cases, where order or chaos shapes the observed morphologies.

Key words. galaxies: kinematics and dynamics – galaxies: spiral – galaxies: structure – ISM: kinematics and dynamics

1. Introduction

In the present paper we call *ordered* spirals those that have as building block a set of stable periodic orbits. The standard example are the spirals in Contopoulos & Grosbøl (1986) models, which end at their inner 4:1 resonance. In this type of models the spiral structure terminates at a distance beyond which there are no more quasiperiodic orbits trapped around stable, elliptical periodic orbits of the x_1 family. On the other hand we will call *chaotic* spirals those that we believe are constituted from stars in chaotic motion. Kaufmann & Contopoulos (1996) argued for the first time that part of the spirals in barred-spiral systems with a single pattern speed are chaotic. The galactic morphologies we study are grand design independently of whether their spirals are ordered or chaotic. We use response models in trying to model these morphologies. The potentials we use are either analytic forms that describe the structures we study, or potentials that have been directly determined from near-infrared observations of specific galaxies.

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2. Normal spiral galaxies

Normal spiral galaxies have no or very weak bar components. Orbital models (Patsis et al. 1991) and gaseous response models (Patsis et al. 1994, 1997a) have shown that open, grand design, *normal* spiral galaxies are best modeled by slowly rotating patterns. Then corotation is beyond the end of the spiral arms, or at least beyond the end of a characteristically bisymmetric part of the arms. Since the

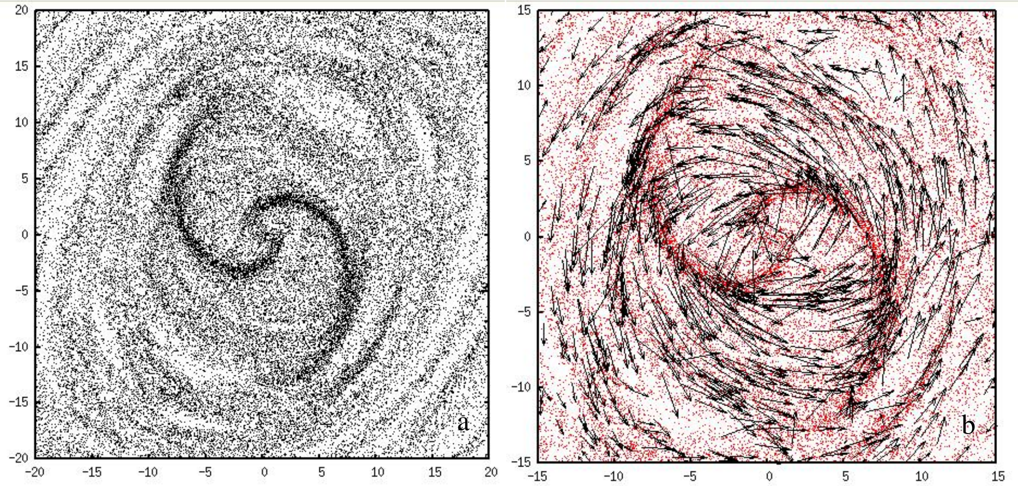

Fig. 1. The flow of stars in a time-independent stellar response model of Contopoulos & Grosbøl (1986) type. (a) The response morphology. Corotation is at ≈ 24 kpc and at the end of the strong spirals, at ≈ 12.5 kpc, is the inner 4:1 resonance. (b) The velocity field of the model indicated by arrows.

galaxies we refer to are grand design, their symmetric part dominates their morphology. Nevertheless, especially in gaseous response models, bifurcations of the arms appear at the end of the symmetric part. Also off-phase extensions of the spirals with respect to the imposed potential minima may appear beyond the point at which symmetry breaks. The inclusion of an $m = 1$ component in phase with the main $m = 2$ spiral and with the same pattern speed, is crucial for modeling the observed structures (see Fig. 4 in Patsis et al. 1997a). The point at which the symmetric part of the spirals ends can be used for the estimation of their pattern speed, since it is associated with the inner 4:1 resonance (Contopoulos & Grosbøl 1986). Very frequently we observe there a characteristic bifurcation of the arms.

In the last 12 years, stellar and gaseous response models for normal spirals, or for spirals that have their own pattern speeds in barred-spiral systems, consistently put corotation beyond the end of the symmetric part of the spirals and in some cases even beyond the end of the spiral structure altogether (Mulder & Combes 1996; Kranz et al. 2001; Bissanz et al. 2003; Kranz et al. 2003; Pichardo et al. 2003; Martos et al. 2004; Martos & Yanez 2005; Vorobyov 2006; Vorobyov & Shchekinov 2006; Minchev & Quillen 2008; Patsis et al. 2009). All these models strongly indicate that the flow in normal spirals follows ‘precessing ellipses’. Since the arms extend inside corotation, they are located in a disk region, where order dominates and thus structures can be built by quasi-periodic orbits trapped around stable periodic orbits.

Fig. 1 shows a typical stellar response model to an imposed bisymmetric potential of the type used by Contopoulos & Grosbøl (1986). Only an $m = 2$ term is included. Corotation is at 24 kpc. The main spirals end at their inner 4:1 resonance, inside corotation (Fig. 1a) and the flow of the stars is along ‘precessing ellipses’ (Fig. 1b).

3. Barred spiral galaxies

Bars end close, but before, corotation (Contopoulos 1980). In barred-spiral systems with one pattern speed and the observed spiral arms attached to the ends of the bar, the spirals have to cross the corotation region where chaos dominates. We present the orbits that we find to support such a spiral structure in

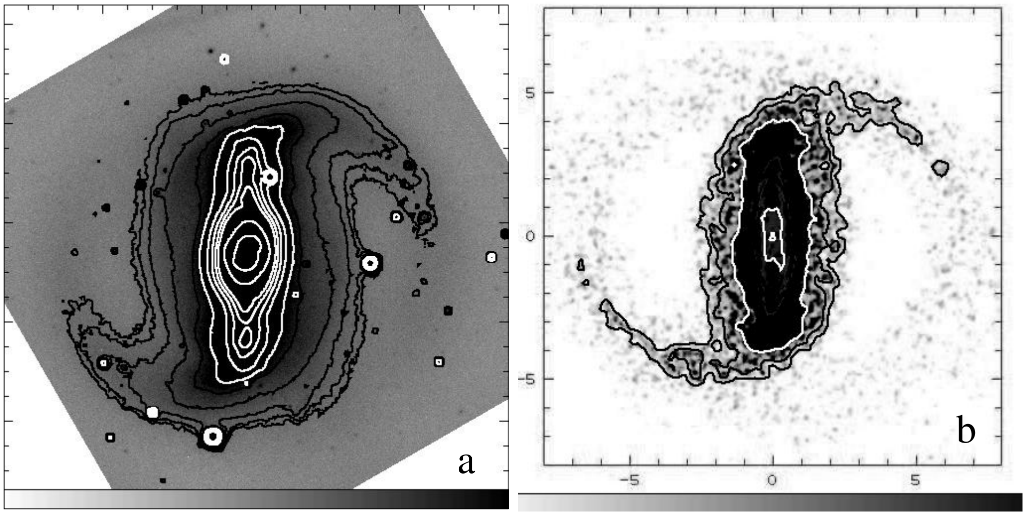

Fig. 2. (a) An *R*-band image of NGC 4314 showing the boxiness of the outer isophotes of the bar. We observe the limited azimuthal extent of the spirals. (b) A stellar response model of the Quillen et al. (1994) potential. The pattern rotates with $\Omega_p = 38.23$ km s^{-1} kpc^{-1}. The model reproduces the basic morphological features of the galaxy.

two types of barred-spiral potentials. Both of them result from near-infrared observations of real galaxies. The values of the pattern speeds (Ω_p) we use in the examples we present below does not necessarily give the best fit of the galaxy morphology in all cases. We just use template models to present the orbital behavior in barred-spiral systems with boxy bars and with bars with ansae morphology.

3.1. Boxy bars

We call 'boxy' the bars that have, on the plane of the galaxy, outer isophotes with rectangular-like shape. A standard example is the nearly face-on, early type barred-spiral galaxy NGC 4314. In Fig. 2a we give an R-image (Gadotti & de Souza 2006) with overplotted isophotes showing the boxiness in discussion. The spiral structure appears as a continuation of the bar and is confined azimuthally in an angle less than $\pi/2$. Patsis et al. (1997b), have shown that the stellar orbits associated with the observed boxy isophotes are chaotic. The potential used for this study has been estimated by Quillen et al. (1994) from the *K*-image of NGC 4314. Stellar responses are similar for a range of Ω_p values $38 < \Omega_p < 45$ km s^{-1} kpc^{-1}. The pattern in the response model of Fig. 2b rotates with $\Omega_p = 38.23$ km s^{-1} kpc^{-1}. Patsis (2006) has shown that the chaotic orbits that reinforce the outer boxy isophotes of the bar are practically the same, which sustain also the spirals that emerge from the ends of the bar. They belong to a population that visits both the bar and the disk area further out. During the time these chaotic orbits visit the bar region, they have a morphological resemblance with quasi-periodic orbits trapped around rectangular-like 4:1 type stable periodic orbits we find in generic barred potentials (Contopoulos 1988). However, in the potential we study, this family is stable over a tiny energy interval, and the space their invariant curves occupy in the phase space is tiny (Patsis et al. 1997b). In Fig. 3 we give characteristic examples of or-

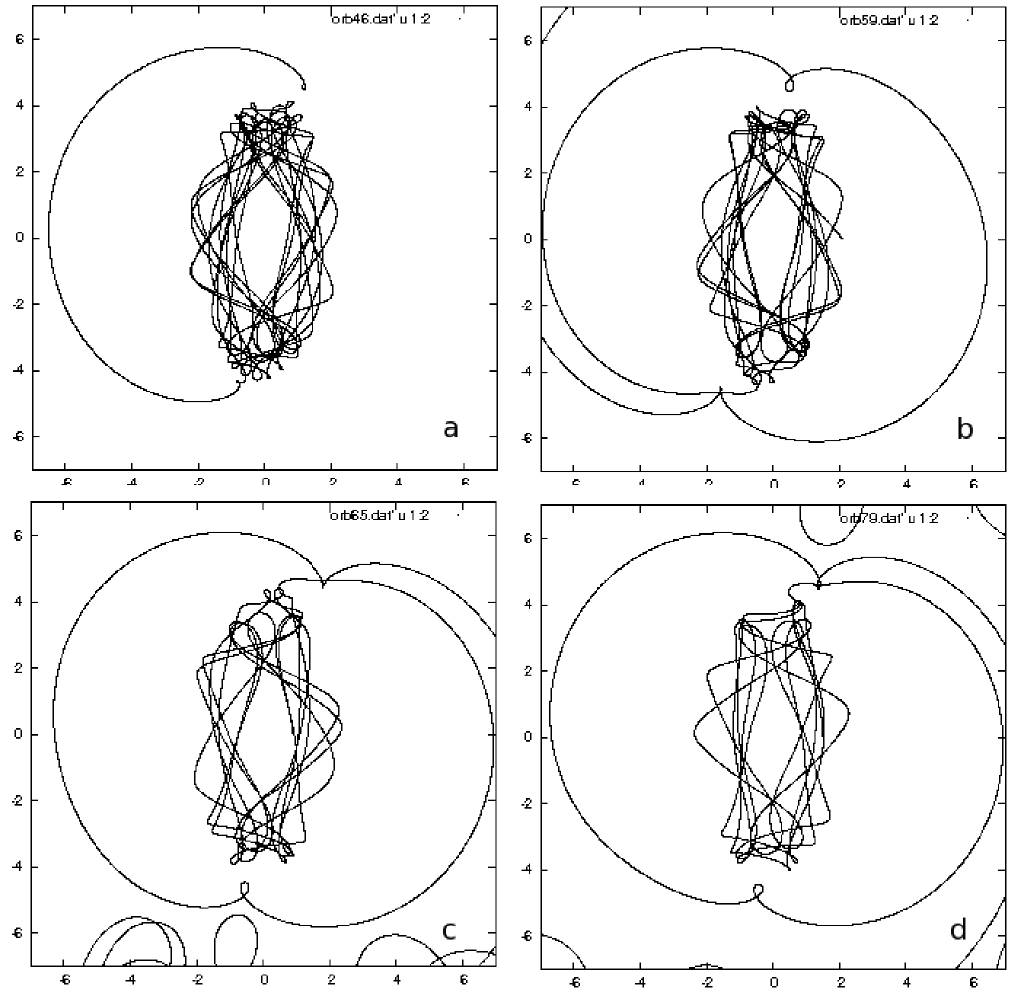

Fig. 3. Chaotic orbits of particles that support the spiral structure we observe in Fig. 2. During the time they spend in the bar region they have a rectangular-like morphology, typical of orbits at the 4:1 region of bars. They are integrated for 10 bar periods.

bits of particles that are located on the spiral arms in Fig. 2b.

3.2. Bars with ansae

Another type of barred-spiral morphology we have studied has an ansae type bar. The potential we used in this case is from an estimation of the potential of NGC 1300, from a *K*-band image of this galaxy (Kalapotharakos et al. 2008). For the figures we present below we have used as inclination and position angles for the bar $42\overset{\circ}{.}2$ and $100\overset{\circ}{.}6$ respectively. The *K*-band image of the galaxy deprojected with these values is given in Fig. 4.

It is interesting that in these models we find qualitatively different effective potentials for nearby values of $\Omega_{\rm p}$. In Fig. 5 we give the

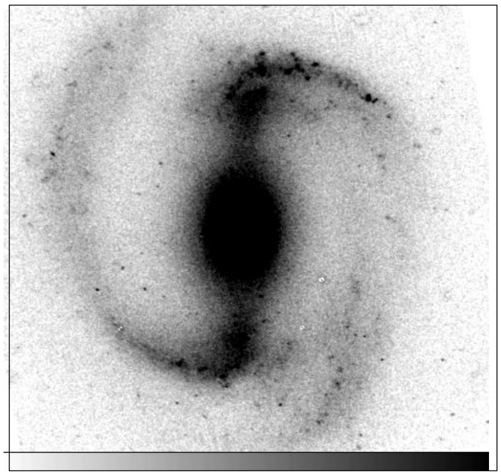

Fig. 4. The deprojected *K*-band image of the barred-spiral galaxy NGC 1300, which we used for our calculations in potentials with ansae type bars.

isocontours of two effective potentials we studied. In Fig. 5a, Ω_p=21 km s^{-1} kpc^{-1}, while in (b) Ω_p=26 km s^{-1} kpc^{-1}. In the case with Ω_p=26 km s^{-1} kpc^{-1} the model has two sets of unstable Lagrangian points, and the ansae morphology appears also in the isocontours. Nevertheless, when Ω_p=21 km s^{-1} kpc^{-1}, we have a more conventional configuration with two unstable Lagrangian points close to the ends of the bar. The models are asymmetric, because in the Fourier analysis we have taken into account also the odd terms (Kalapotharakos et al. 2008). Despite the differences these two models give similar stellar responses. Again here we consider the orbits that support the spirals found. They are chaotic and their typical morphologies can be seen in Fig. 6. As in the previous barred-spiral case we have orbits that visit both the bar region as well as the disk beyond its end. During the time they stay at the bar region they develop a morphology which again has a 4:1 resonance character. However, this morphology is not rectangular-like, but like another type of 4:1 orbits. These are elliptical-like with loops at their apocentra (Contopoulos 1980; Patsis et al. 1997b). These chaotic orbits shape also the ansae, performing a number of loops at the corresponding regions.

4. Other cases

4.1. Barred galaxies with extended spiral structure

In both barred-spiral galaxies we have studied above, the spiral arms are radially and/or azimuthally confined to short distances. Especially in NGC 1300, the spiral structure is very asymmetric. The right arm, as depicted in Fig. 4, practically breaks in two parts. In NGC 4314, the extent of the spirals azimuthally does not exceed $\pi/2$. This is a morphology that differs from the logarithmic spirals of nearly normal grand design spiral galaxies, where we do not observe major gaps (Grosbøl & Patsis 1998). A case of a barred-spiral system with a radially extended spiral structure without major gaps and discontinuities along the arms, has been studied by Boonyasait et al. (2005) and Patsis et al. (2009) using a potential estimated from near-infrared observations of NGC 3359. For these 'well organized' spiral arms the best matching of the flow at their region has been obtained by a 'precessing-ellipses' flow. The spiral structure in the barred-spiral galaxy NGC 3359 is supported by regular orbits. This is an indication that there is a correspondence between morphological features of the arms (extent, presence of gaps etc.) and the dynamical mechanism that sustains them in each individual case.

4.2. Normal double spirals

As we have noted in Sect. 2, in both gaseous and stellar response models of normal open spirals we find the density response maxima along the imposed potential minima only up to the inner 4:1 resonance. Beyond that distance we find in some cases off-phase extensions between the 4:1 resonance and corotation in gaseous models. Nevertheless, if we fine tune our models, so that we have a perturbing force of the order of 10% of the axisymmetric background at corotation, and populate the region beyond corotation with enough particles,

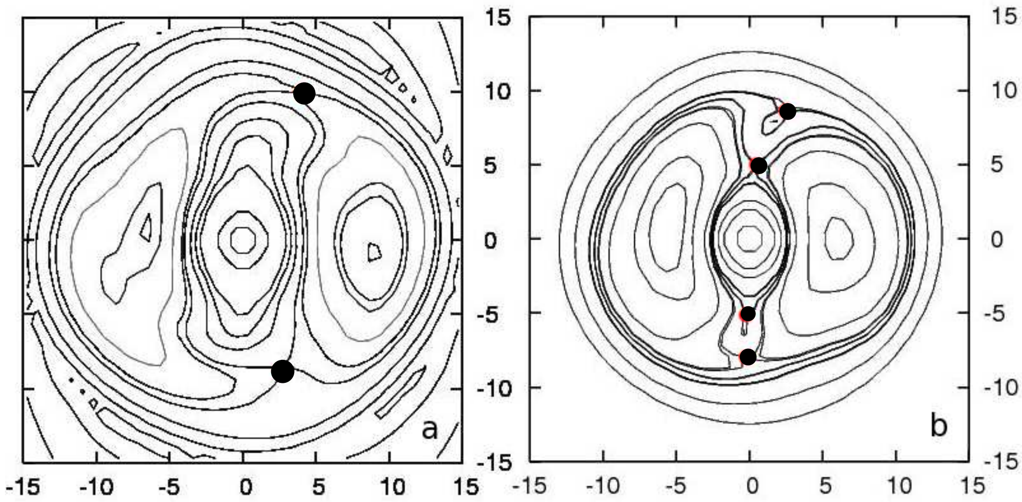

Fig. 5. Equipotentials of effective potentials in models for NGC 1300. In (a) Ω_p=21 km s^{-1} kpc^{-1} and in (b) Ω_p=26 km s^{-1} kpc^{-1}. Heavy dots indicate the unstable Lagrangian points in the two models.

we observe another set of spirals *beyond* corotation. These spirals are weak and do not have the pitch angle of the imposed potential. This is the case depicted in Fig. 7.

The strong spirals we observe in Fig. 7a end at the 4:1 resonance and are supported by regular orbits. The weak spirals beyond corotation, emerge close to the unstable Lagrangian points of the system and follow a chaotic flow, which is shown in Fig. 7b. Double spirals in response models with a gap at the corotation region are obtained also by Vorobyov (2006). These morphologies are not frequently observed. However, grand design spiral galaxies like NGC 1566 and NGC 5248 show this morphology and are candidates of hosting both ordered and chaotic spirals.

5. Conclusions and discussion

The orbital response models that we have studied lead us to the following conclusions:

1. Response models of (nearly) normal grand design spiral galaxies indicate that the spiral arms in this type of galaxies rotate slowly. Corotation is beyond the end of the bisymmetric part of the spirals and the grand design is supported by regular orbits. There are several published simulations in the literature that reproduce this result. As soon as the perturbing forces are larger than 5% of those of the axisymmetric background, the nonlinear phenomena described by Contopoulos & Grosbøl (1986) are present in the models. The final response morphology is obtained after a few pattern rotations. This means that these models can predict galactic morphologies that last for a few Gyr.
2. Barred-spiral systems with a single pattern speed may have spirals that are supported by chaotic orbits. In the cases we have studied and we have found that the spirals are supported by particles in chaotic motion (NGC 4314, NGC 1300), the spiral arms are either confined azimuthally in their extent, or asymmetric with gaps. Contrarily in a barred-spiral galaxy with a well described spiral structure (NGC 3359) our results are in agreement with a flow of regular orbits. The conditions under which barred-spiral systems have ordered or chaotic spirals needs further investigation. We men-

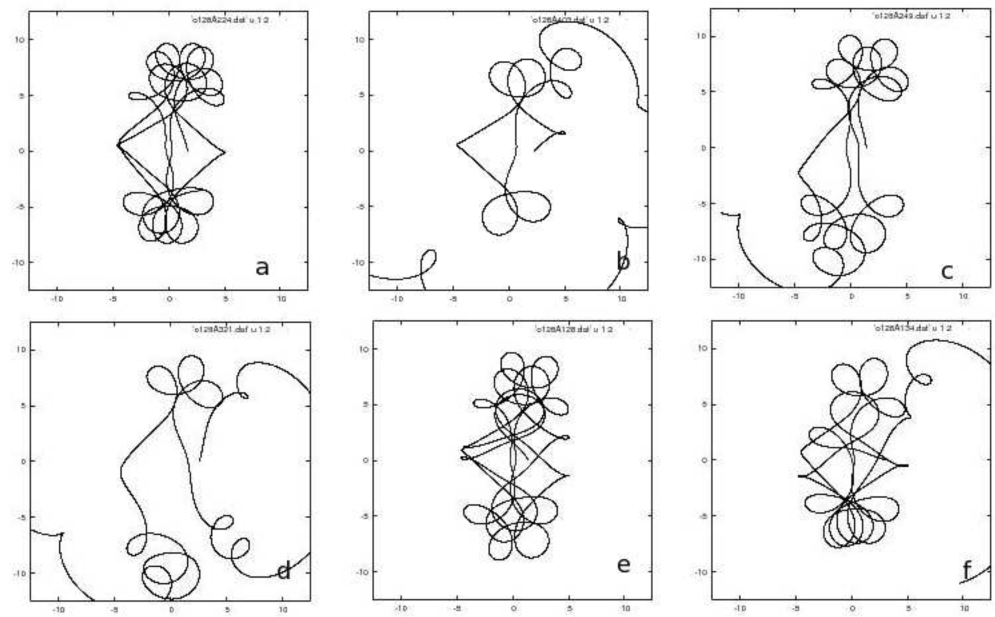

Fig. 6. Typical orbits that support barred-spiral morphologies with ansae. They support both the spirals as well as the ansae features. They are integrated for 10 bar periods.

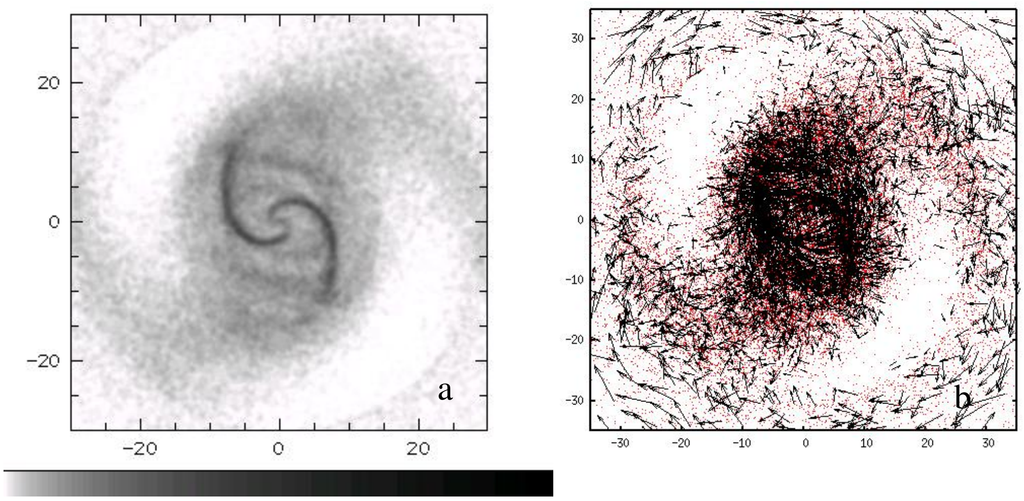

Fig. 7. A model of a double normal spiral. In (a) we observe the inner strong and the outer weak spiral. In (b) we give the velocity field with arrows, so that we can see the flow along the spirals beyond corotation.

tion the work of other groups based on N-body models and orbital theory that present models of barred-spiral systems with a well developed spiral structure consisting entirely by particles in chaotic motion (see Efthymiopoulos et al. 2008 and references therein, as well as Romero-Gomez et al. 2008 and references therein).

3. The chaotic orbits that support the spirals belong to a population that visits both the bar and the disk region beyond corotation. In the two examples we studied we find that they are the same orbits that shape the outer structure of the bars. They support the boxy and the ansae type morphologies of our models. This means that they belong to a very important orbital population for understanding the shapes of the bars. On a surface of section we find the initial conditions in a chaotic sea, that support the bar if integrated for a certain number of bar revolutions (of the order of 10). During the time these orbits stay at the bar region, they follow trajectories with a morphology similar to those of 4:1 resonance regular orbits trapped around stable periodic orbits. This gives to the bars shapes resembling periodic orbits at the 4:1 resonance region.

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