RevMexAA (Serie de Conferencias), **46**, 65–68 (2015)

STELLAR ORBITAL STUDIES IN NORMAL SPIRAL GALAXIES: EFFECT OF SPIRAL ARMS ON DISK DYNAMICS

A. Pérez-Villegas[1], B. Pichardo[2], and E. Moreno[2]

RESUMEN

Hemos construído una familia de modelos no axisimétricos para galaxias espirales normales. En estos potenciales hemos empleado un modelo tridimensional autogravitante para los brazos espirales (PERLAS). Con esta familia de modelos, analizamos la dinámica estelar sobre el plano del disco, variando parámetros estructurales y dinámicos tales como el ángulo de enrollamiento, masa del brazo y la velocidad angular. Para el ángulo de enrollamiento, encontramos dos límites. El primero, basado en el comportamiento ordenado, a través de la cosntrucción de órbitas periódicas se muestra que para ángulos de enrollamiento hasta de ∼ 15°, ∼ 18° y ∼ 20°, para galaxias Sa, Sb y Sc, respectivamente; los brazos espirales podrían ser estructuras de larga duración, más allá de estos límites los brazos espirales podrían ser explicados como estructuras transitorias. El segundo límite está basado en el comportamiento caótico, por medio de un estudio en el espacio fase, encontramos que el límite para el águlo de enrollamiento antes de que el caos destruya a los brazos espirales es de ∼ 30°, ∼ 40° y ∼ 50°, para galaxias Sa, Sb y Sc, respectivamente. Finalmente, estudiamos la dinámica orbital variando tanto la masa del brazo espiral como la velocidad angular, con el objetivo de encontrar restricciones a estos parámetros en diferentes tipos morfológicos. Con estos estudios, notamos que el efecto que los brazos espirales producen en la dinámica del disco estelar al variar la masa o la velocidad de los brazos, esta fuertemente ligada con el ángulo de enrollamiento.

ABSTRACT

We have built a family of non-axisymmetric potential models for normal non-barred spiral galaxies. For this purpose, a three-dimensional self-gravitating model of spiral arms (PERLAS) is used. We analyze the stellar dynamics on the disk plane, varying structural and dynamical parameters such as pitch angle, strength of spiral arms and angular speed. For the pitch angle, we found two limits. The first limit, based on ordered behavior, periodic orbit studies show that for pitch angles up to approximately 15°, 18°, and 20° for Sa, Sb and Sc galaxies, respectively, the spiral arms could be long-lasting structures. Beyond those limits, spiral arms may be explained as transient features rather than long-lasting large-scale structures. In a second limit, from a phase space orbital study based on chaotic behavior, we found that for pitch angles larger than ∼ 30°, ∼ 40° and ∼ 50° for Sa, Sb, and Sc galaxies, respectively, chaotic orbits dominate all the prograde phase space region that surrounds the periodic orbits sculpting the spiral arms, and can even destroy them. Finally, we studied orbital dynamics varying other parameters such as the pattern speed and the spiral arm mass; also we looked for restrictions for these parameters in different morphological types. In these studies we noticed that the effect of spiral arms on the disk dynamics, when we vary the pattern speed and mass, is strongly linked to the pitch angle.

Key Words: chaos — galaxies:evolution — galaxies:kinematics and dynamics — galaxies: spirals — galaxies: structure

1. INTRODUCTION

For many years astronomers have devoted a great effort to classify galaxies. The most used classification of galaxies has been the Hubble sequence (Hubble 1926). This classification scheme of galaxies distinguishes several morphological types: elliptical, normal spiral, barred spiral, and irregular galaxies. Spiral galaxies are classified in the Hubble sequence based mainly on two criteria: the pitch angle and the bulge-to-disk luminosity ratio. Therefore, normal (and barred) spiral galaxies go from early to late, i.e. from large total mass, massive bulges and closed spiral arms to small masses, lighter bulges and open spiral arms. However, in "real life" the Hubble scheme is not closely followed by galaxies, because the structural and dynamical parameters present a large scatter among galaxies catalogued within the same mor-

---

[1] Centro de Radioastronomía y Astrofísica, Universidad Nacional Autónoma de México, Apartado Postal 3–72, 58090, Morelia, Michoacán, México (a.perez@crya.unam.mx).

[2] Instituto de Astronomía, Universidad Nacional Autónoma de México, A.P. 70-264, 04510, México D.F., México (barbara@astro.unam.mx).

phological type. The pitch angle is the parameter with the widest scatter, going from about 4° to 50° (Kennicutt 1981; Ma et al. 2000; Davis et al.2012). Also, the Hubble sequence is satisfactory for galaxies with redshift $z < 0.5$ (van den Bergh 2002), where (non-interacting) galaxies have had time to relax. As a first approximation we adopted the ideal Hubble morphological scheme to study the effects of orbital structure in different spiral galaxies.

This work is devoted to structural and dynamical parameters of spiral arms. These are: pitch angle, mass, and angular speed. With this detailed orbital study of order and chaos we wanted to elucidate the influence of spiral arms on different morphological types of galaxies, as we go from early to late types; to provide some restrictions on structural and dynamical parameters; and to produce a set of parameters for allowed spiral models, self-consistent from an orbital point of view (periodic orbits), with good probability of being long-lasting structures, and mild or quiet chaotic nature.

2. NUMERICAL IMPLEMENTATION AND METHODOLOGY

We have constructed a family of models for the potential of normal spiral galaxies (Sa, Sb, and Sc), as classified by Hubble (1926), and also based on recent observational parameters taken from the literature (Table 1). For this purpose, we numerically solved the equations of motion for stars in an axisymmetric potential plus a spiral arm potential. The methods that we use in this work to study stellar dynamics in the disk plane are periodic orbits analysis, maximum density response, and Poincaré diagrams.

2.1. *Models for Normal Spiral Galaxies*

The galactic models are formed by two parts: the axisymmetric and non-axisymmetric components. The axisymmetric component consists of a bulge and a disk of the form given by Miyamoto-Nagai (1975), and a supermassive spherical halo (Allen & Santillán 1991). The non-axisymmetric potential is the three-dimensional, self-gravitating model of spiral arms given by Pichardo et al. (2003), called PERLAS. This model is a mass distribution formed by a set of inhomogeneous oblate spheroids lying on a logarithmic spiral locus.

In Table 1 we present the observational and theoretical parameters employed to fit the galactic models and their respective references.

2.2. *Methods for the Stellar Orbital Analysis*

For the stellar orbits dynamical analysis we employed periodic orbits, density response, and Poincaré diagrams. We have calculated the density response using the method of Contopoulos & Grosbol (1986), which quantifies the support of spiral arms with periodic orbits. We computed approximately 50 periodic orbits per phase-space diagram. The density response is defined as the region where periodic orbits crowd producing a density enhancement. The position of the maximum density response along each periodic orbit is calculated, and with these positions the locus formed by the maxima of density response is found and compared with the position of the imposed spiral locus.

Regarding the Poincaré diagrams, these are made in the space of positions and velocities (x', v'_x) in the non-inertial reference system that rotates with the spiral arms. Poincaré diagrams have two regions: a prograde region (left side of the diagram), where the stars move in the same direction than the rotation of the spiral arms, and a retrograde region (right side of the diagram), where the stars move in opposite direction to the rotation of the spiral arms. Each Poincaré diagram contains 50 orbits, distributed between the prograde and retrograde regions, with 350 points each (points correspond to the number of periods).

3. RESULTS

We carried out an extensive orbital study with periodic orbits, density response, and phase-space diagrams to determine whether limiting values to structural and dynamical parameters of normal spiral galaxies can be establish. The restrictions we found included variations in the pitch angle, mass and angular speed, we did two orbital studies in order to analyze the effect of each parameter. One of them is based on ordered behavior (with periodic orbits and density response) and the second one is based on chaotic behavior (with phase space diagrams).

Figure 1 shows the limits for the pitch angle for each morphological type. For the limit based on ordered behavior, the periodic orbit studies show that for pitch angles up to ∼ 15°, ∼ 18°, and ∼ 20° for Sa, Sb and Sc galaxies (top panels in Figure 1), respectively, the density response (where the orbits crowd producing a density enhancement) supports closely the spiral arms potential at all radii, a requisite for the existence of a long-lasting large-scale spiral structure. Beyond those limits, the density response tends to “avoid” the potential imposed by maintaining lower pitch angles in the density response; in that case the spiral arms may be explained as transient features rather than long-lasting large-scale structures.

TABLE 1

PARAMETERS OF THE GALACTIC MODELS

Parameter	Value			Reference
	Sa	Sb	Sc	
		Axisymmetric Components		
$\mathrm{M_D/M_H}$ [a]	0.07	0.09	0.1	4,8
$\mathrm{M_B/M_D}$	0.9	0.4	0.2	5,8
Rotation Velocity ^{3}($\mathrm{km\,s^{-1}}$)	320	250	170	7
$\mathrm{M_D}$ ($10^{10}\mathrm{M_\odot}$)	12.8	12.14	5.10	4
$\mathrm{M_B}$ ($10^{10}\mathrm{M_\odot}$)	11.6	4.45	1.02	$M_\mathrm{B}/M_\mathrm{D}$ based
$\mathrm{M_H}$ ($10^{11}\mathrm{M_\odot}$)	16.4	12.5	4.85	$M_\mathrm{D}/M_\mathrm{H}$ based
Disk Scale-Length (kpc)	7	5	3	4,5
		Spiral arms		
Locus	–	Logarithmic	–	1,9,10
Arms Number	–	2	–	2
Pitch Angle i (°)	7 – 20	10 – 20	15 – 30	3,7
$\mathrm{M_{sp}/M_D}$	–	0.01 – 0.10	–	–
Scale-Length (kpc)	7	5	3	Disk based
Ω_p ^{1} ($\mathrm{km\ s^{-1}\,kpc^{-1}}$)	–	-10 to -60	–	1,6

[a] Up to 100 kpc halo radius.

References: (1) Grosbøl & Patsis 1998; (2) Drimmel et al. 2000; Grosbøl et al. 2002; Elmegreen & Elmegreen 2014; (3) Kennicutt 1981; (4) Pizagno et al. 2005; (5) Weinzirl et al. 2009; (6) Patsis et al. 1991; Grosbøl & Dottori 2009; Egusa et al. 2009; Fathi et al. 2009; Gerhard 2011; (7) Brosche 1971; Ma et al. 2000; Sofue & Rubin 2001; (8) Block et al. 2002; (9) Pichardo et al. 2003; (10) Seigar & James 1998; Seigar et al. 2006.

From a phase space orbital study based on chaotic behavior, we found that for pitch angles larger than ∼ 30°, ∼ 40° and ∼ 50° for Sa, Sb, and Sc galaxies (bottom panels in Figure 1), respectively, chaotic orbits dominate all the phase space prograde region that surrounds the periodic orbits sculpting the spiral arms and can even destroy them. This result seems to be in good agreement with observations of pitch angles in typical isolated normal spiral galaxies.

We repeated the same study of the pitch angle, this time with the mass of the spiral arms and their angular speed, and we obtained a set of valid parameters for spiral arms. For more details about the restrictions on structural and dynamical parameters in normal spiral galaxies see Pérez-Villegas et al. (2012, 2013, 2015).

4. CONCLUSIONS

In this contribution we have presented the following results:

- With the use of a steady physical model to simulate normal spiral galaxies, we studied the disk dynamics as we vary structural and dynamical parameters: the pitch angle, mass and angular velocity.
- Based on ordered behavior, we found limits for spiral arm parameters where spiral arms could be either a long-lasting structure or could instead be explained as a transient feature.
- Based on chaotic behavior, we found limits where spiral arms can be destroyed, because chaos becomes pervasive, destroying all orbital support.
- In these studies, we noticed that the effect that spiral arms induce on the dynamics of the disk is strongly linked to the pitch angle, when we vary the pattern speed or the mass of spiral arms.
- The ratio M_{sp}/M_D in early spiral galaxies could be larger than in late spiral galaxies, without compromising the stability, i.e., if the pitch angle is smaller, the limit of the mass of spiral arms could be higher.

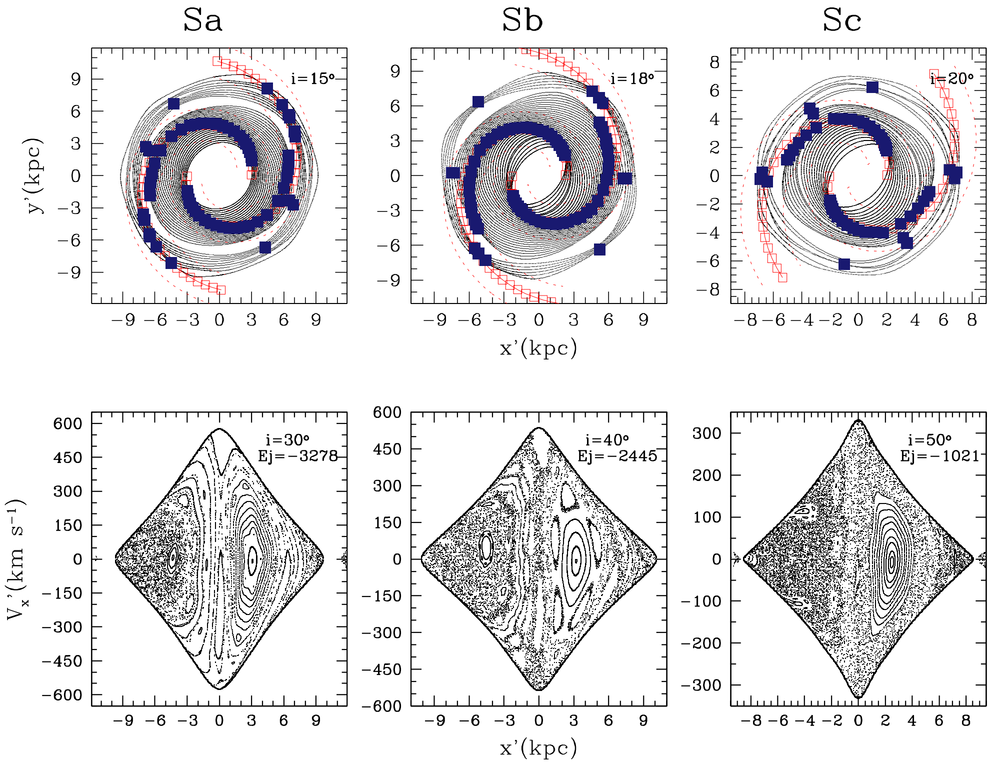

Fig. 1. Top panels show periodic orbits, response maxima (filled squares) and the imposed spiral locus (open squares) for pitch angles of 15°, 18° and 20° for Sa, Sb and Sc galaxies, respectively. Bottom panels show the phase space diagrams with $E_J = -3278, -2545$ and -1021×10^2 km^2 s^{-2}, for the pitch angles of 30°, 40° and 50° for Sa, Sb and Sc galaxies, respectively.

- The effect of angular speed is almost negligible. However, this is an important parameter because it establishes the extension of spiral arms, therefore the angular velocity should not be too fast nor too slow.

REFERENCES

Allen, C. & Santillán, A. 1991, RMxAA, 22, 256
Block, D. L. et al. 2002,A&A, 394, L35
Brosche, P. 1971, A&A, 13, 293
Contopoulos, G. & Grosbøl, P., 1986, A&A, 155, 11
Davis, B. L. et al. 2012, ApJS, 199, 33
Drimmel, R. 2000, A&A, 358, L13
Egusa, F., Kohno, K., Sofue, Y., Nakanishi, H., & Komugi, S. 2009, ApJ, 697, 1870
Elmegreen, D. M., & Elmegreen, B. G. 2014, ApJ, 781, 11
Fathi, K. et al. 2009, ApJ, 704, 1657
Gerhard, O. 2011, Memorie della Societa Astronomica Italiana Supplementi, 18, 185
Grosbøl, P., & Dottori, H. 2009, A&A, 499, L21
Grosbøl, P. J., & Patsis, P. A. 1998, A&A, 336, 840
Grosbøl P., Pompei E., & Patsis, P., 2002, ASP Conf. Ser., 275, 305
Hubble, E. P. 1926, ApJ, 64,321
Kennicutt, R. 1981, AJ, 86, 1847
Ma, Jhun, Zhao, Jun-liang, Zhang, Fei-peng, & Peng, Qiu-he 2000, Chinese Astronomy and Astrophysics, 24, 435
Miyamoyo, M., & Nagai, R., 1975, Pub. Astr. Soc. Japan, 27, 533
Patsis, P. A., Contopoulos, G. & Grosbøl P., 1991, A&A, 243, 373
Pérez-Villegas, A. et al. 2012, ApJ, 745, L14
Pérez-Villegas, A., Pichardo, B., & Moreno, E. 2013, ApJ, 772, 91
Pérez-Villegas, A., Pichardo, B., & Moreno, E. 2015, submitted to ApJ
Pichardo, B., Martos, M., Moreno, E. & Espresate, J. 2003, ApJ, 582, 230
Pizagno, J. et al. ApJ, 633, 844
Seigar, M. S., & James, P. A. 1998, MNRAS, 299, 685
Seigar, M. S., Bullock, J. S., Barth, A. J., & Ho, L. C. 2006, ApJ, 645, 1012
Sofue, Y. & Rubin, V. 2001, ARA&A, 39, 137
van den Bergh, S. 2002, PASP, 114, 797
Weinzirl, T., Jogee, S., Khochfar, S., Burket, A. & Kormendy, J. 2009, ApJ, 696, 411