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MODELLING THE INNER PARTS OF THE MILKY WAY USING INVARIANT MANIFOLDS

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RESUMEN

En una serie de artículos propusimos una teoría que puede explicar la formación y propiedades de tanto los anillos como los brazos espirales en galaxias barradas. Los bloques principales de estas estructuras son órbitas atrapadas por las variedades invariantes de las órbitas periódicas alrededor de los puntos Lagrangianos inestables situados al final de la barra. Aquí presentamos una comparación de la morfología de las espirales observadas y de las teóricas. Describimos el mecanismo de formación usado para obtener estas estructuras y comparamos tanto la morfología como la cinemática de los anillos y espirales teóricos con los datos observacionales. Finalmente, introducimos el trabajo reciente para modelizar brazos espirales de la Vía Láctea usando esta aproximación.

ABSTRACT

In a series of papers we proposed a theory to explain the formation and properties of rings and spirals in barred galaxies. The building blocks of these structures are orbits trapped by the invariant manifolds of the periodic orbits around the unstable Lagrangian points located near the ends of the bar. Here, we will first present a comparison of the morphology of observed and theoretical spirals and rings. We will describe the mechanism used to obtain these features and then we will compare the morphology and kinematics of the rings and spirals obtained with the ones from observations. Finally, we will introduce the work done to model the spiral arms of the Milky Way using this new approach.

Key Words: galaxies: kinematics and dynamics — galaxies: structure — Galaxy: kinematics and dynamics — Galaxy: structure

1. INTRODUCTION: WHAT ARE THE INVARIANT MANIFOLDS?

Here we present the results from modelling the spiral arms and rings of barred galaxies using invariant manifolds. This is a summary of the main results given in Romero-Gómez et al. (2006, 2007), Athanassoula, Romero-Gómez, & Masdemont (2009), and Athanassoula et al. (2009, 2010). The invariant manifolds can be described as flux orbits that guide the motion around the unstable Lagrangian points L_1 and L_2. This is an alternative way different from the density wave theory to explain the spiral arms and rings in barred galaxies.

To compute the invariant manifolds, we will consider a galactic potential composed of an axisymmetric component plus another bar-like. In the rotating reference frame, the bar is fixed and along the x-axis, the effective potential has five equilibrium points: L_1 and L_2 are located along the semi-major axis of the bar and are saddle points, L_3 is located at the centre of the galaxy, L_4 and L_5, along the semi-minor axis of the bar, and are stable elliptic points. There exists a family of unstable periodic orbits around $L_1(L_2)$, starting with the energy of the equilibrium point. These orbits cannot trap material around them, however, there exists another family of orbits linked to the periodic orbits called invariant manifolds. Roughly speaking, the invariant manifolds are a set of orbits that depart (unstable branches) or approach (stable branches) the periodic orbit of the saddle point. Each of the manifolds has two branches: one going to the inner parts of the galaxy and the other, to the outer parts of the galaxy. The general view of the manifolds has an x-shape, describing the typical behaviour of the saddle point.

In our previous work, we vary the main free parameters, that is, the bar mass/amplitude and the

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bar pattern speed, and we obtain invariant manifolds of different shapes, i.e., two spiral arms, outer rings whose principal axis is perpendicular to the bar major axis (R_1 rings), outer rings whose principal axis is parallel to the bar major axis (R_2 rings), and in few cases, the two types of outer rings together (R_1R_2 rings).

2. MAIN CHARACTERISTICS OF THE INVARIANT MANIFOLDS

The orbits trapped by the manifolds are closely related to the instability of the equilibrium point, and as it increases, the global shape of the galaxy changes from being a closed R_1 ring to open spiral arms to R_2 and R_1R_2 rings. So the time it takes and orbit to perform a revolution and to have the global shape, also depends on the instability of the equilibrium point, being the spiral arms faster, of the order of 3–4 bar revolutions, and the rings slower to form, of the order of 6–8 bar revolutions (Romero-Gómez et al. 2006).

The circulation of the stars along the manifolds is also different depending on whether the global morphology is a ring or spiral arms (Athanassoula et al. 2010). The circulation in the case of R_1 rings is closed, i.e., once the star is trapped by the manifolds, it will stay there forever. The spiral arms case is different. First, the circulation is along the spiral arms, which makes it different from the density wave theory. Secondly, the stars trapped by the manifolds originally come from the inner parts of the bar or from the outer parts of the disc and are trapped by the manifolds when the bar is forming, circulating from the inner parts towards the outer parts of the disc.

Finally, the effect of the gas on the orbits trapped by the manifolds is tested in Athanassoula et al. (2010). We simulate the shocks of the gas by making the particle lose a fraction of kinetic energy at random positions during the integration. The effect on the global morphology is that the thickness of the spiral arm or ring decreases, i.e., we obtain thinner structures.

3. THE INVARIANT MANIFOLDS AND THE INNER PART OF THE GALAXY

Here we present the preliminary results of computing the invariant manifolds to a galactic potential originally set to describe the Milky Way (Romero-Gomez et al., in preparation). We use a composite inhomogeneous prolate bar (Pichardo et al. 2004), PMM04. We first consider only the Galactic bar in the potential, and then we modify this by adding the

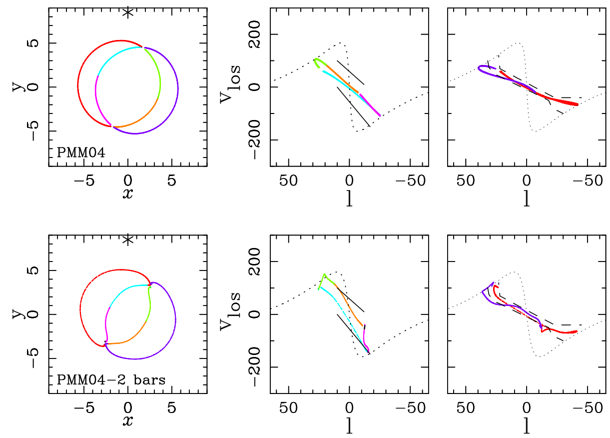

Fig. 1. Longitude-velocity diagrams. Top panel: single bar case. Bottom panel: the case with the 2 bars at an angular separation of 20°. The Sun is located on the y-positive axis (marked with an asterisk) and the Galactic bar is located at 20° from the Sun – Galactic Center direction. The bar pattern speed is 45 km s^{-1} kpc^{-1}.

Long bar. We use the same parameters as the ones selected by the authors and we compute the orbits trapped by the manifolds and the galactic longitude – line-of-sight velocity diagram, (l, v). In the first columns of Figure 1, we show the orbits in the (x, y) plane, each colour representing a part of the structure. In the middle panel, we plot only the (l, v) diagram of the inner branches, while in the right panel, we plot the kinematics of the outer branches. The solid and dashed lines in both panels mark the observational constraints, the 3 kpc arm and the Galactic Molecular Ring, respectively. Note that the case with only one bar, it does not reproduce well the 3 kpc arm, while when the Long bar is introduced, the inner branches become more elongated and the velocities better reproduce the observed features.

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