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Escape dynamics in a binary system of interacting galaxies

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HIGHLIGHTS

- A binary galaxy model of interacting galaxies is used.
- We investigate the escape dynamics of stars in the binary system.
- We locate the several basins of escape and we relate them with the corresponding escape times.

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ABSTRACT

The escape dynamics in an analytical gravitational model which describes the motion of stars in a binary system of interacting dwarf spheroidal galaxies is investigated in detail. We conduct a numerical analysis distinguishing between regular and chaotic orbits as well as between trapped and escaping orbits, considering only unbounded motion for several energy levels. In order to distinguish safely and with certainty between ordered and chaotic motion, we apply the Smaller ALingment Index (SALI) method. It is of particular interest to locate the escape basins through the openings around the collinear Lagrangian points L_1 and L_2 and relate them with the corresponding spatial distribution of the escape times of the orbits. Our exploration takes place both in the configuration (x, y) and in the phase $(x, \dot{x})$ space in order to elucidate the escape process as well as the overall orbital properties of the galactic system. Our numerical analysis reveals the strong dependence of the properties of the considered escape basins with the total orbital energy, with a remarkable presence of fractal basin boundaries along all the escape regimes. It was also observed that for energy levels close to the critical escape energy the escape rates of orbits are large, while for much higher values of energy most of the orbits have low escape periods or they escape immediately to infinity. We hope our outcomes to be useful for a further understanding of the escape mechanism in binary galaxy models.

1. Introduction

Over the years many studies have been devoted on the issue of escaping particles from dynamical systems. Especially the issue of escapes in Hamiltonian systems is directly related to the problem of chaotic scattering which has been an active field of research over the last decades and it still remains open (e.g., Bleher et al., 1988; Jung and Scholz, 1988; Contopoulos and Kaufmann, 1992; Benet et al., 1998; Motter and Lai, 2002; Seoane et al., 2006; 2007; Seoane and Sanjuán, 2008; Seoane et al., 2009; Seoane and Sanjuán, 2010). The problem of escape is a classical problem in simple Hamiltonian nonlinear systems (e.g., Aguirre et al., 2001; Aguirre and Sanjuán, 2003; Aguirre et al., 2009; Barrio et al., 2008; Blesa et al., 2012; Zotos, 2014a) as well as in dynamical astronomy (e.g., Hut and Bahcall, 1983; Benet et al., 1996; 1998; de Moura and Letelier, 2000; Zotos, 2012a). Escaping orbits in the classical restricted three-body problem (RTBP) is another typical example (e.g., Nagler, 2004; 2005; de Assis and Terra, 2014).

Nevertheless, the issue of escaping orbits in Hamiltonian systems is by far less explored than the closely related problem of chaotic scattering. In this situation, a test particle coming from infinity approaches and then scatters off a complex potential. This phenomenon is well investigated as well interpreted from the viewpoint of chaos theory (e.g., Bleher et al., 1988; 1990; 1989; Jung, 1987; Jung et al., 1999; 1995; Jung and Pott, 1989; Jung and Richter, 1990; Jung and Scholz, 1987; Jung and Tel, 1991; Lai et al., 2000; 1993; Lau et al., 1991; Lipp and Jung, 1999).

In open Hamiltonian systems an issue of great importance is the determination of the basins of escape, similar to basins of attraction in dissipative systems or even the Newton–Raphson fractal structures. An escape basin is defined as a local set of initial conditions of orbits for which the test particles escape through a certain exit in the equipotential surface for energies above the escape value. Basins of escape have been studied in many earlier papers (e.g., Bleher et al., 1988; Contopoulos, 2002; Kennedy and Yorke, 1991; Poon et al., 1996). The reader can find more details regarding basins of escape in

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Contopoulos (2002), while the review (Zotos, 2014b) provides information about the escape properties of orbits in a multi-channel dynamical system composed of a two-dimensional perturbed harmonic oscillator. The boundaries of an escape basins may be fractal (e.g., Aguirre et al., 2009; Bleher et al., 1988) or even respect the more restrictive Wada property (e.g., Aguirre et al., 2001), in the case where three or more escape channels coexist in the equipotential surface.

Escaping and trapped motion of stars in stellar systems is an another issue of great importance. In a previous article Zotos (2012a), we explored the nature of orbits of stars in a galactic-type potential, which can be considered to describe local motion in the meridional (R, z) plane near the central parts of an axially symmetric galaxy. It was observed that apart from the trapped orbits there are two types of escaping orbits, those which escape fast and those which need to spend vast time intervals inside the equipotential surface before they find the exit and eventually escape. The escape dynamics and the dissolution process of a star cluster embedded in the tidal field of a parent galaxy were investigated in Ernst et al. (2008). Conducting a scanning of the available phase space the authors managed to obtain the basins of escape and the respective escape rates of the orbits, revealing that the higher escape times correspond to initial conditions of orbits near the fractal basin boundaries. The investigation was expanded into three dimensions in Zotos (2015) where we revealed the escape mechanism of three-dimensional orbits in a tidally limited star cluster. Furthermore, Ernst and Peters (2014) explored the escape dynamics in the close vicinity of and within the critical area in a two-dimensional barred galaxy potential, identifying the escape basins both in the phase and the configuration space.

The numerical approach of the above-mentioned papers serves as the basis of this work. The main objective of our numerical exploration is to determine which orbits escape and which remain trapped, distinguishing simultaneously between regular and chaotic trapped motion. Furthermore, we shall try to locate the escape basins which reflect the orbital structure of the system and they also determine through which channel the orbit escape to infinity. To our knowledge, this is the first that the escape dynamics of a binary system of interacting galaxies is numerically investigated. Our work is quite similar to Zotos (2015) where we studied the escape process in a star cluster rotating around its parent galaxy. In Zotos (2015) however, the dynamical system had three degrees of freedom (3D), while the present one is only two-dimensional (2D).

The article is organized as follows: In Section 2 we present in detail the structure and the properties of our binary galaxy model. All the computational methods we used in order to determine the nature of orbits are described in Section 3. In the following section, we conduct a systematic numerical investigation revealing the overall orbital structure (bounded regions and basins of escape) of the binary galaxy and showing how it is affected by the total orbital energy. Our paper ends with Section 5, where the discussion and the main conclusions are given.

2. The binary galaxy model

The aim of this research is to explore the properties of motion in the planar softened circular restricted three-body problem. Our analytic gravitational model consists of a pair of dwarf spheroidal galaxies. The two spheroidal galaxies move in circular orbits around their common center of gravity, which is assumed to be fixed at the origin $(0, 0)$ of the coordinates. The third body (a star test particle) moves in the same plane under the gravitational field of the two galaxies. As a first step we shall consider the case where the two galaxies are identical (same mass, same structure) similarly to the Copenhagen case of the classical RTBP.

To model the dynamical properties of the spheroidal galaxies we use the well known spherically symmetric Plummer potential (Plummer, 1911). Therefore, the potential which describes the motion around the first galaxy (hereafter galaxy G_1) is given by the equation

$$\Phi_1(x, y) = \frac{-GM_1}{\sqrt{R^2 + c_1^2}}, \tag{1}$$

where $R^2 = x^2 + y^2$, while M_1 is the mass and c_1 the core radius of galaxy G_1. Similarly, galaxy G_2 is described by the potential

$$\Phi_2(x, y) = \frac{-GM_2}{\sqrt{R^2 + c_2^2}}, \tag{2}$$

where M_2 is the mass and c_2 the core radius of galaxy G_2. The core radius c_i acts as a softening parameter which eliminates the problem of critical collision orbits which is present in the classical RTBP.

We shall apply the theory of the softened circular restricted three-body problem. The two galaxies move in circular orbits in an inertial frame OXYZ with the origin at the center of mass of the system with a constant angular velocity $\Omega_{\rm p} > 0$, given by Kepler's third law

$$\Omega_{\rm p} = \sqrt{\frac{GM_t}{d^3}}, \tag{3}$$

where $M_{\rm t} = M_1 + M_2$ is the total mass of the system, while d is the distance between the centers of the two bodies. A clockwise, rotating frame Oxyz, is used with the axis Oz coinciding with the axis OZ and the axis Ox coinciding with the straight line joining the centers of two galaxies. In this frame, which rotates with angular velocity $\Omega_{\rm p}$, the two centers have fixed positions $C_1(x, y) = (x_1, 0)$ and $C_2(x, y) = (x_2, 0)$, respectively. The total gravitational potential which is responsible for the motion of a star in the dynamical system of the binary galaxy is

$$\Phi_{\rm t}(x, y) = \Phi_1(x, y) + \Phi_2(x, y) + \Phi_{\rm rot}(x, y), \tag{4}$$

where

$$\Phi_1(x, y) = \frac{-GM_1}{\sqrt{R_1^2 + c_1^2}},$$

$$\Phi_2(x, y) = \frac{-GM_2}{\sqrt{R_2^2 + c_2^2}},$$

$$\Phi_{rot}(x, y) = -\frac{\Omega_p^2}{2}(x^2 + y^2), \tag{5}$$

and

$$R_1^2 = (x - x_1)^2 + y^2, \quad R_2^2 = (x - x_2)^2 + y^2, \tag{6}$$

with

$$x_1 = -\frac{M_2}{M_t}\, d, \quad x_2 = R - \frac{M_2}{M_t}\, d = d + x_1. \tag{7}$$

In our study we use a system of galactic units where the unit of length is 20 kpc, the unit of mass is $1.8 \times 10^{11} M_{\odot}$ and the unit of time is 0.99×10^8 years. The velocity unit is 197 km/s, while G is equal to unity ($G = 1$). In these units, we use the values: $M_1 = M_2 = 1$, $c_1 = c_2 = 0.2$ and $d = 2$. The values of these quantities remain constant throughout securing also positive mass density everywhere and free of singularities. The fact that the two galaxies are sufficiently apart from each other ($d = 40$ kpc) allow us to assume that the tidal phenomena are very small and therefore negligible.

The two galaxies move around their common mass center of the system with angular velocities Ω_{p1} and Ω_{p2}, given by

$$\Omega_{\rm p1} = \sqrt{\frac{1}{x_1}\left(\frac{-d\Phi_2(R)}{dR}\right)_{R=d}},$$

$$\Omega_{\rm p2} = \sqrt{\frac{1}{x_2}\left(\frac{d\Phi_1(R)}{dR}\right)_{R=d}}. \tag{8}$$