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Tails and bridges in the parabolic restricted three-body problem

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ABSTRACT

After a close encounter of two galaxies, bridges and tails can be seen between or around them. A bridge would be a spiral arm between a galaxy and its companion, whereas a tail would correspond to a long and curving set of debris escaping from the galaxy. The goal of this paper is to present a mechanism, applying techniques of dynamical systems theory, that explains the formation of tails and bridges between galaxies in a simple model, the so-called parabolic restricted three-body problem, i.e. we study the motion of a particle under the gravitational influence of two primaries describing parabolic orbits. The equilibrium points and the final evolutions in this problem are recalled,and we show that the invariant manifolds of the collinear equilibrium points and the ones of the collision manifold explain the formation of bridges and tails. Massive numerical simulations are carried out and their application to recover previous results are also analysed.

Key words: methods: numerical – celestial mechanics – galaxies: interactions.

1 INTRODUCTION

Gaia data release 1 has reported very recently the discovery of tails around the Large and Small Magellanic Clouds (a pair of massive dwarf galaxies) as well as an almost continuous stellar bridge between them (see Belokurov et al. 2017). Actually, in the seventies, the observation of tails and bridges in multiple galaxies was already recorded. We mention the interacting pairs M51 and NGC 5195 or the pair of interconnected galaxies Arp 295 as two particular examples (see Toomre & Toomre 1972 and references therein). These papers argue that tails and bridges are just tidal relics of close encounters between two galaxies. In order to study the effects of the brief but violent tidal forces due to a close encounter between the galaxies, several authors have considered a very simple model: each encounter involves only two galaxies assumed to describe parabolic orbits, and each galaxy is idealized as just a disc of non-interacting test particles that initially orbit a central mass point. This model corresponds to the parabolic restricted three-body problem (the *parabolic problem* along the paper), assuming that the two-point primaries are the galaxies describing parabolic orbits around their common centre of mass.

There are several studies of the observable bridges and tails in galaxies. For instance, Condon et al. (1993) show that galaxies UGC 12914 and UGC 12915 have a continuum bridge that is thought to be due to the collision of the galaxies 2×10^7 years ago, considering that the orbits are nearly parabolic. In Günthardt et al. (2006), the authors consider the system AM1003-435 that is composed by two interacting galaxies. They studied the dynamical evolution of the encounter between the galaxies to conclude that they were moving in parabolic orbits. The *N*-body simulation of the orbits of stars in the galaxies shows bridges and tails. Also using the parabolic model, Namboodiri, Kochhar & Alladin (1987) studied the existence of bridges and tails in interacting galaxies depending on the circular velocity of the stars within the galaxies.

The parabolic model has also been used in the study of close encounters between disc-surrounded stars and the formation of planets. Pfalzner et al. (2005) studied the change of mass between stars when one or both of them are surrounded by a disc of low-mass particles. They concluded that, in the coplanar case, there were more change of particles between stars when the encounter was prograde. Fragner & Nelson (2009) studied the effect of parabolic encounters in the formation of Jovian-mass planets. They concluded that planets that have been formed after encounters are more massive and also have greater semimajor axes. Steinhausen, Olczak & Pfalzner (2012) studied the influence on the initial density of the particles in the change of mass between star-disc encounters, concluding that the shape of the mass distribution has a high effect on the final outcome. Finally, Faintich (1972) considered a Sun–star–comet system to determine the effect of the stellar encounter on the trajectory of the comet but considering a hyperbolic model instead of a parabolic one.

The goal of this paper is, applying techniques of dynamical systems theory, to describe a mechanism that explains the formation of bridges and tails in the very simple model of the parabolic problem. Without trying to make a definition, a *bridge* would be an arm

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