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Evolution of trojan exoplanets in protoplanetary discs

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Abstract

Despite the existence of co-orbital bodies in the solar system, and the prediction of the formation of co-orbital planets by planetary system formation models, no co-orbital exoplanets (also called trojans) have been detected so far. We investigate how a pair of trojan exoplanets would fare during their migration in a protoplanetary disc. To this end, we start with an analytical study of the evolution of two planets near the Lagrangian equilibria L_4 and L_5, identifying for which values of the parameters these equilibria are either attractive or repulsive. We then compare these results to hydrodynamical simulations. Finally, we study the evolution of co-orbital configurations using a planetary system formation model that simulates the orbital evolution of the planet over the disc lifetime. Depending on the parameters of the disc, and the orbital parameters and masses of the planets, the system can either evolve toward the Lagrangian equilibrium, or tend to increase its amplitude of libration, possibly all the way to horseshoe orbits or even exiting the resonance. The stability in the direction of the eccentricities and the inclinations is also studied.

1. Introduction

Celestial bodies in co-orbital configurations are common in the solar system: the Earth, Mars, Jupiter, Uranus and Neptune have known co-orbital asteroids (also called trojans in the case of Jupiter). Two bodies of comparable masses can be in a co-orbital configuration as well: it is the case of the Saturnian moons Janus and Epimetheus, that have a mass ratio of ≈ 3.5 and are on a horseshoe orbit around Saturn. Co-orbital exoplanets are a common outcome of planetary system formation models [1,2], which typically yield co-orbital exoplanets in a few percent up to a few tens of percent of the created systems. All that being said, no co-orbital exoplanets have been found so far, despite survey missions such as Kepler that found hundreds of multi-planetary systems. Potential observational biases and adapted detection method were discussed in previous studies [3,4]. Here we discuss how dissipation affects the co-orbital resonance, particularly in the case of migration in protoplanetary discs, for small inclinations and eccentricities.

2. Method

Using the formalism developed in [5], we start by studying the behaviour of this resonance in the vicinity of the L_4 and L_5 Lagrangian equilibria. We develop an analytical model of the co-orbital resonance with a generic form of dissipation:

$$\begin{aligned} \dot{a}_j &= -a_j/\tau_{a_j} = -a_j/(\tau_{w_j} a_j^k)\,, \\ \dot{e}_j &= -e_j/\tau_{e_j}\,, \\ \dot{I}_j &= -I_j/\tau_{I_j}\,, \end{aligned} \tag{1}$$

where a, e, I are the semi-major axes, eccentricities, and inclinations of the planets, and the τ are migration and damping timescales. We then study the stability of the L_4 and L_5 equilibria in three directions: the 'circular' direction, associated to the semi-major axis and resonant angle; the direction associated with the eccentricities; and the one associated with the inclinations. Depending on the value of the masses of the co-orbitals and the strength of the dissipation of the different orbital elements, we show that the system can evolve toward the equilibria, or away from them, in the various directions.

In order to apply these results to the evolution of planets in protoplanetary discs, we study the evolution of co-orbital planets in the disc using short-duration 2-D hydrodynamic simulations. In this set of simulations, we explore the indirect effect of the planets on one another through perturbation of the protoplanetary discs. Two cases are studied: the type 1 migration, where both planets are embedded in the disc, and the type 2 migration, where one or both planets opened a gap in the disc.

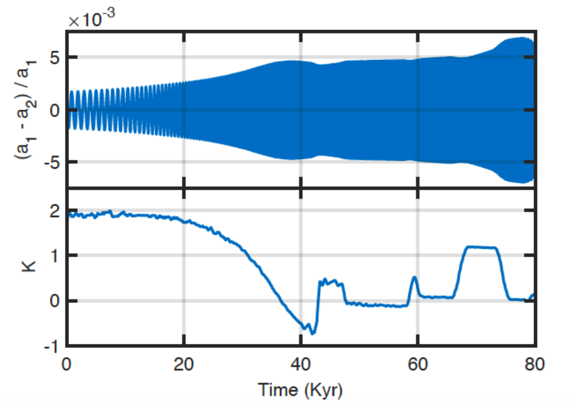

Figure 1: Top: libration around the exact resonance for a pair of coorbitals ($m_1 = 2m_2 = 20m_{Earth}$) embedded in a protoplanetary disc that evolves in time. Bottom: value of the parameter k, function of the disc parameters. For this value of the masses, the Lagrangian equilibria are attractive when $k < 0$, and repulsive otherwise.

Finally, we study the behaviour of co-orbital configurations in a 1-D evolving disc, that simulates the orbital evolution of the planet throughout the disc lifetime. We again study both types of planet migration, but over a much larger timescale than is computationally feasible for hydrodynamic simulations. The larger time-scales allow us to follow the evolution of the co-orbital planets as they migrate into different regions of the disc, which can have vastly different dissipation rates that thus significantly affect the evolution of the co-orbital system (Figure 1).

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3. Results

For given masses of the planets we identified for which value of the parameter k (defined in equation 1) the Lagrangian equilibria are attractive or repulsive.

In the case of type 1 migration, k is a function of the local disc density profile and temperature profile. In this regime, the behaviour of the co-orbital resonance is hence predictable from the parameters of the disc and the mass of the planets (Figure 1). In type 2 migration, our analysis rely mainly on the result of the hydrodynamical simulations.

This work hence allows to identify general trends, such as the range of expected amplitude of libration for the resonant angle as a function of the mass of the planets. In certain cases, evolution toward inclined co-orbitals, or eccentric ones, is also possible. These results help to explain the absence of certain configuration of co-orbital exoplanets, and might prove useful to develop adapted detection methods for the hunt for the first co-orbital exoplanet [6].

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