Planetary and Space Science xxx (2018) 1–8

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Co–orbital resonance with a migrating proto–giant planet

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ARTICLE INFO

Keywords:
Celestial mechanics
Minor planets
Planet
Disc interactions

ABSTRACT

In this work we pose the possibility that, at an early stage, the migration of a proto–giant planet caused by the presence of a gaseous circumstellar disk could explain the continuous feeding of small bodies into its orbit. Particularly, we study the probability of capture and permanence in co–orbital resonance of these small bodies, as planets of diverse masses migrate by interaction with the gaseous disk, and the drag induced by this disk dissipates energy from these small objects, making capture more likely. Also, we study the relevance of the circumplanetary disk, a structure formed closely around the planet where the gas density is enhanced, in the process of capture. It is of great interest for us to study the capture of small bodies in 1:1 resonance because it could account for the origin of the Trojan population, which has been proposed (Kortenkamp and Joseph, 2011) as a mechanism of quasi-satellites and irregular satellites capture.

1. Introduction

It is now widely accepted that the planetary systems, and particularly our Solar System, were not formed in an *in–situ* scenario. On the contrary, these planets underwent a substantial migration of their orbits. This migration may have different origins, such as interactions with a gaseous (Goldreich and Tremaine, 1979, 1980) or planetesimal (Fernandez and Ip, 1984) disk. The presence of these structures imply that the migration must have taken place in the early Solar System.

Nevertheless, the actual path of each planet still remains as an open question. One of the models explaining this process is the *Jumping–Jupiter* model (Morbidelli et al., 2009), where the young Solar System contains 5 giant planets. These planets migrate through interaction with a planetesimal disk and becomes unstable, and due to this instability, the four giant planets present nowadays have encounters with the fifth one, acquiring orbits similar to the ones we observe in the present and ejecting the remaining one. Besides explaining the orbital characteristics of the giant planets, this model have been successfully applied to explain the origin of many small bodies population in our Solar System (Nesvorný et al., 2013, 2014; Brasil et al., 2014; Deienno et al., 2014), as well as the Late Heavy Bombardment (Deienno et al., 2017). On the other side, the constraints given by the observations of the present Solar System impose a large number of conditions to be met by the results of simulations to be considered as successful, which make this model unlikely (Nesvorný and Morbidelli, 2012).

Although a model of capture in co–orbital motion in the frame of the Jumping–Jupiter scenario (i.e., involving the encounter of Jupiter with an ice giant) has been proposed (Nesvorný et al., 2013), we pose the hypothesis that a population of planetesimals could be captured in the co–orbital region of the migrating planet before the instability, when the capture could be assisted by the drag force exerted on the planetesimals by the gaseous disk. In a subsequent stage, the particles captured as Trojans can transform their orbits into quasi-satellites, which in turn enables them to have close encounters with the host planet (Kortenkamp and Joseph, 2011).

In this work we investigate two different stages of the capture process. Firstly, we analyse the probability of capture in the planet's co–orbital region. A planetesimal is said to be captured if it enters and stays in the co–orbital region for a certain period of time, which implies a change in semi–major axis of the bodies. It is worth noting that, in this scenario, this drift is produced by two different mechanisms: for the planet, it is caused by the gravitational interaction with the disk, while the aerodynamical gas drag is the reason for the migration of planetesimals. The different migration timescales involved can account for the continuous feeding of bodies in the mentioned region, where they can be captured in resonance. In second place, we study the survivability of planetesimals in this region once they are captured.

The outline of this study is as follows: In Section 2 we present the hypothesis and model setup used for this work. In Section 3 we analyse the results of the simulations made, looking for captures in co–orbital resonance and their dependence on the presence of a gas disk along with the migration timescale, and study the survivability of these bodies.

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https://doi.org/10.1016/j.pss.2018.06.004
Received 13 November 2017; Received in revised form 9 April 2018; Accepted 5 June 2018
Available online xxxx
0032-0633/

Please cite this article in press as: Lemos, P., Gallardo, T., Co–orbital resonance with a migrating proto–giant planet, Planetary and Space Science (2018), https://doi.org/10.1016/j.pss.2018.06.004

Finally, we present the conclusions, discussion and future work in Section 4.

2. Methods

2.1. Disk parameters

In this work we study 3 different cases for the gas drag: Experiment A has no presence of any gas, so the forces acting on the planetesimals are only of gravitational origin. We use this prescription as a control run, to test the effect of the gas. Experiments B and C use a circumstellar (CS) disk of gas where the radial distribution of surface density is

$$\Sigma_s(r) = 1700\left(\frac{r}{1ua}\right)^{-3/2} gcm^{-2} \tag{1}$$

which corresponds to the Minimum Mass Solar Nebula (Weidenschilling, 1977). The vertical distribution of the volume density is given by

$$\rho(z) = \rho_0 e^{-z^2/2h^2} \tag{2}$$

where $\rho_0 = \rho(z=0)$ is the mid–plane density and h is the vertical scale height. When a vertically isothermal disk is assumed, $h = c_s/\Omega$, where c_s is the sound speed and $\Omega = \sqrt{GM_\odot/r^3}$ is the Keplerian angular velocity, the relation between surface and volume density is

$$\rho_0 = \frac{1}{\sqrt{2\pi}}\frac{\Sigma_s}{h} \tag{3}$$

Besides this circumstellar disk, Experiment C uses a circumplanetary (CP) disk following Fujita et al. (2013). In that work, the density and sound speed of the circumplanetary disk are parametrized as

$$\Sigma_p = \Sigma_d\left(\frac{r}{r_d}\right)^{-p}, \quad c_s = c_d\left(\frac{r}{r_d}\right)^{-q/2} \tag{4}$$

where $r_d \equiv dr_H$ is a typical length scale related to the Hill radius r_H, approximately equal to the effective size of the circumplanetary disk, and c_d is the sound speed at this point. In this work we set $p = 3/2$, $d = 0.4$ and $q = 1/2$ based on the result of previous hydrodynamical simulations (Machida et al., 2008). Lastly, we choose $\Sigma_d = 1.0\, g\, cm^{-2}$ following Fujita et al. (2013). The inclusion of this circumplanetary disk is important because the planetesimals are expected to enter in the co–orbital region nearby the embryo, and the enhanced energy dissipation provided by this structure could modify substantially the dynamics of these bodies.

Lastly, we dealt with the gas velocity. Due to the gas pressure support, the velocity of the gas around the central star is not Keplerian. Using the parametrization given in 4, the gas velocity in Experiments B and C can be written as

$$v_g = v_K(1-\eta) \tag{5}$$

where v_K is the Keplerian velocity around the central star or embryo in Experiments B or C respectively, and η is given by (Tanaka et al., 2002)

$$\eta = \frac{1}{2}\frac{h^2}{r^2}\left(p + \frac{q+3}{2} + \frac{q}{2}\frac{z^2}{h^2}\right) \tag{6}$$

The solid bodies that reach a radius $s \simeq 1\, m$ become less coupled with the gas, orbiting the central star with a Keplerian velocity, to the first approximation. This means that there exist a difference between the velocities of gas and rocks, which leads to a friction force, called *gas drag*. The gas drag force for a spherical particle of radius s is given by

$$F_g = -\frac{1}{2}C_D\, \pi s^2\, \rho \Delta v^2 \tag{7}$$

where dimensionless parameter C_D is the *drag coefficient*, ρ is the gas density and Δv is the relative velocity of the particle with respect to the gas.

2.2. Orbital dynamics simulations

For this work we use the *Mercury* package (Chambers, 1999). The system is composed by a giant planet embryo ($M_P = 10M_\oplus$) in a circular orbit with semi–major axis of 8 *au*, and migrates with a constant rate of $1.5\times 10^{-5}\, au\, yr^{-1}$, consistent with the rate found by Tanaka et al. (2002). This migration rate is achieved by imposing an acceleration $\mathbf{a_M}$ of the form

$$\vec{a}_M = \frac{\dot{a}}{2a^2}\sqrt{\frac{GM_\odot}{2/r - 1/a}}\hat{v} \tag{8}$$

acting only on the embryo. Although this force does not represent any actual physical effect, it generates the desired migration rate with minimal impact over the remaining orbital elements. It is important to note that in this work we neglect the embryo's mass growth. The linear model used by Tanaka et al. (2002) to derive the migration rate for the embryo assumes an isothermal equation of state, not only vertically but also in the radial direction. Nevertheless, this model has numerous caveats (disks are probably turbulent and non–isothermal, there exist considerable uncertainties in the formulas used to compute torques exerted by the disk, etc.) which could introduce variations in the rates found. For this reason we add an ad–hoc constant coefficient k to Equation (8) to investigate the relevance of the migration timescale on our scenario in all the simulations made, where the values adopted for k were 1, 0.1 and 1.5.

We generate a swarm of 1000 planetesimals within a ring between 6 and 10 *au* with eccentricities and inclinations randomly chosen with a uniform distribution in the interval $[0, 0.1]$ and $[0^\circ, 10^\circ]$ respectively. For the purpose of calculation of the gas drag force given in Equation (7), C_D was chosen to be equal to unity, and we assumed a spherical shape for the planetesimals, with radius uniformly distributed between $50\, m$ and $35\, km$, and a uniform density of $1\, g/cm^3$. Using these prescriptions, the total mass of the planetesimal disk is approximately $2.2\times 10^{-11} M_\odot$.

We integrate the system for 10^5 years using the Bulirsch-Stoer algorithm (Stoer et al., 2002), along with user-defined forces to take account of both migration and gas drag. Although this is the slowest algorithm implemented on Mercury, is especially suitable for dealing with close encounters, which is fundamental for this work.

3. Captures and survivability

3.1. Co–orbital capture

The first condition to obtain bodies captured in co–orbital resonance is that the orbits of the planetesimals cross the orbit of the embryo. If the semi–major axis of a planetesimal is initially larger (smaller) than the embryo's, and in some moment of its evolution become smaller (larger), the body is said to have a crossing orbit. In Experiment A we expect to find a greater number of planetesimals with orbits initially internal to the embryo to become crossing bodies because only the latter has an external force modifying its orbit. However, in Experiments B and C we expect to find the opposite, as the planetesimals migration timescale due to the gas drag is shorter. This different migration rates generate a rapid variation in the semi–major axis ratio between planetesimals and embryo, which implies in addition to a possible crossing orbit, a mean motion resonance capture. For this reason we also look for bodies captured in mean motion resonances with the embryo for at least 1000 years. If the resonances are identified as $|p+q| : |p|$, where p is the degree and $q > 0$ the order, $p > 0$ implies that the planetesimal has an orbit internal to the embryo and $p < 0$ the opposite. We look for all the possible resonance captures with $p \in [-11, 10]$ and $q \le 10$. The next condition analysed is the co–orbital capture. For a capture in co–orbital resonance to take place, we impose