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Planetesimal-driven planet migration in the presence of a gas disk

Christopher C. Capobianco [a,*], Martin Duncan [a], Harold F. Levison [b]

[a] Department of Physics, Engineering Physics and Astronomy, Queens University, 99 University Avenue, Kingston, Ontario, Canada K7L 3N6
[b] Southwest Research Institute, Department of Space Studies, 1050 Walnut Street, Suite 429, Boulder, CO 80302, USA

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ABSTRACT

We report here on an extension of a previous study by Kirsh et al. (Kirsh, D.R., Duncan, M., Brasser, R., Levison, H.F. [2009]. Icarus 199, 197–209) of planetesimal-driven migration using our *N*-body code SyMBA (Duncan, M.J., Levison, H.F., Lee, M.H. [1998]. Astron. J. 116, 2067–2077). The previous work focused on the case of a single planet of mass M_{em}, immersed in a planetesimal disk with a power-law surface density distribution and Rayleigh distributed eccentricities and inclinations. Typically 10^4–10^5 equal-mass planetesimals were used, where the gravitational force (and the back-reaction) on each planetesimal by the Sun and planet were included, while planetesimal–planetesimal interactions were neglected. The runs reported on here incorporate the dynamical effects of a gas disk, where the Adachi et al. (Adachi, I., Hayashi, C., Nakazawa, K. [1976]. Prog. Theor. Phys. 56, 1756–1771) prescription of aerodynamic gas drag is implemented for all bodies. In some cases the Papaloizou and Larwood (Papaloizou, J.C.B., Larwood, J.D. [2000]. Mon. Not. R. Astron. Soc. 315, 823–833) prescription of Type-I migration for the planet are implemented, as well as a mass distribution.

In the gas-free cases, rapid planet migration was observed – at a rate independent of the planet's mass – provided the planet's mass was not large compared to the mass in planetesimals capable of entering its Hill sphere. In such cases, both inward and outward migrations can be self-sustaining, but there is a strong propensity for inward migration. When a gas disk is present, aerodynamic drag can substantially modify the dynamics of scattered planetesimals. For sufficiently large or small mono-dispersed planetesimals, the planet typically migrates inward. However, for a range of plausible planetesimal sizes (i.e. 0.5–5.0 km at 5.0 AU in a minimum mass Hayashi disk) outward migration is usually triggered, often accompanied by substantial planetary mass accretion. The origins of this behaviour are explained in terms of a toy model. The effects of including a size distribution and torques associated with Type-I migration are also discussed.

1. Introduction

Currently, over 460 extrasolar planets are known,[1] along with over 40 systems containing multiple planets. Most of the extrasolar planets detected to date have masses comparable to that of Neptune, or larger. Furthermore in a recent summary by Udry et al. (2007), at least ~6% of stars surveyed have giant planets interior to ~5.0 AU, so giant planets appear fairly common in stellar systems. Moreover, results from the HARPS survey, Sousa et al. (2008) shows that Neptune-mass extrasolar planets are found in ~40% of the stars surveyed. Most likely, these giant planets formed via a similar process that formed the four giant planets in the Solar System.

However, the masses and orbits of these extrasolar planets display a wide variety of configurations: e.g. Neptune and Jupiter-mass planets with short orbital periods, isolated planets with large orbital eccentricities, multiple planet systems in resonance, and planets orbiting components of stellar binaries. Several analytical models have been proposed to explain the various aspects of planet formation, but most of these have not been tested numerically. Until recently, very little had been done on giant planet core formation using *N*-body simulations (Thommes et al., 2003). Levison et al. (2010) (hereafter referred to as LTD10) recently completed a comprehensive set of computer simulations which included a number of physical processes that might enhance accretion onto planetary embryos. As discussed in Section 2, the most successful models were those in which one or more embryos spontaneously underwent a burst of outward migration induced by planetesimal scattering.

In an attempt to further our understanding of some of the results in LTD10, we are undertaking a detailed investigation of the combined effects of planetesimal scattering and aerodynamic drag on the growth and evolution of giant planet cores. Our goal in this paper is to understand the case of the dynamics of a single core interacting with a disk of planetesimals and gas. In what follows, we provide some background in Section 2, then briefly discuss

* Corresponding author.
E-mail address: ccapo@astro.queensu.ca (C.C. Capobianco).

[1] See http://exoplanet.eu.

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our implementation of the relevant forces in Section 3. In Section 4 we discuss the results of simulations including aerodynamic gas drag, for a disk of mono-dispersed planetesimals. A toy model which explains the results is presented in Section 5. The effects of a planetesimal size distribution is presented in Section 6, and Type-I migration in Section 7. A summary and conclusion is presented in Section 8.

2. Giant planet formation

The formation of giant planets in the widely adopted core accretion model can typically be described in four stages. The first stage involves the formation of planetesimals, which we do not model in this study. The next stage involves the runaway accretion of planetesimals by a small fraction of those planetesimals which happen to grow a bit larger, and then grow much faster than all the others (Wetherill and Stewart, 1989). When these large bodies become sufficiently massive and well-spaced such that each dominates the viscous stirring in its feeding zone, the runaway growth gives way to the oligarchic growth stage. An embryo's feeding zone is the annulus about its orbit where small bodies can suffer strong gravitational impulses. Typically this feeding zone extends from 1.0 to 3.5 Hill radii on either side of the embryo's orbit, and is the source of most of the material which the embryo accretes. During the oligarchic stage, the large embryos grow in lockstep, maintaining similar masses and uniformly spaced orbits (Kokubo and Ida, 1998; Thommes et al., 2003). The final stage in the outer Solar System is characterized by the rapid accumulation of a gaseous envelope by the embryos; in the inner region it is characterized by the giant impact phase of terrestrial planet formation.

However, the core accretion model has its weaknesses. In particular, the accretion of a massive atmosphere requires a solid core of mass $\sim 10M_\oplus$ to trigger a rapid gas accretion phase (Mizuno, 1980; Pollack et al., 1996; Hubickyj et al., 2005). The difficulties of reaching this threshold are threefold:

(1) Accretion has to be sufficiently efficient to concentrate enough mass into at least one body, and potentially multiple bodies.
(2) Accretion has to occur within ~10 Myr (Haisch et al., 2001), such that there is $\sim 10^2 M_\oplus$ left in the nearby disk to furnish an envelope.
(3) Migration due to embryo–disk tidal interactions (cf. Section 3.2.2), threatens to deposit core-sized bodies into the central star faster than they can accrete (Ward, 1986, 1993; Ward, 1997).

Several analytical models have been proposed to mitigate these problems, and some of these have been tested numerically by LTD10. In particular, LTD10 numerically integrated the orbits of a number of planetary embryos embedded in a swarm of planetesimals. Their simulations included simplified models of various combinations of the following effects: (1) aerodynamic drag on small bodies, (2) collisional damping, (3) extended atmospheres around the embryos (Inaba and Ikoma, 2003), (4) embryo eccentricity damping due to gravitational interaction with the gas disk, (5) fragmentation of the planetesimals and (6) evaporation and recondensation at the snow line (Cuzzi and Zahnle, 2004). They found that the gravitational interaction between the embryos and the planetesimals generally led to regions near the embryos being cleared of planetesimals before much accretion onto the embryos could occur. However, the most successful phases of embryo growth occurred when the gravitational scattering of the planetesimals, together with the effects of aerodynamic gas drag led to the rapid outward migration of one or more embryos. We show in this paper that many of the main features of the embryo–planetesimal interactions that lead to rapid outward migration and planet growth are demonstrated by the single embryo case which we discussed next.

3. Physical processes in circumstellar disks

There are several physical processes that can occur in circumstellar disks; some of these are only relevant to planetesimals, while others only to larger embryo-sized bodies. Specifically, the dynamics of planetesimals and embryos will be affected by the gravitational perturbations from other massive bodies, as well as gas effects. Radiative forces are not very important for 0.01–100 km size bodies over the timescale under consideration (i.e. ~10 Myr), so we neglect such forces in the subsequent discussion.

3.1. Gravitational effects

The dominant gravitational influence in the circumstellar environment, for planetesimals and embryos, is the central star. However, in the vicinity of other massive bodies (e.g. embryos), the gravitational tidal influence of those massive bodies will dominate. The transition is characterized by a length scale called the Hill radius, which defines a sphere about each body where its gravitational tide dominates the gravitational influence from the central star:

$$R_h \equiv a\left(\frac{M}{3M_\star}\right)^{1/3} \tag{1}$$

where M and a are the mass and the semi-major axis of an orbiting body, while $M_\star$ is the mass of the central star. At 1.0 AU an Earth-mass object would have $R_h \simeq 0.01$ AU, while at 10.0 AU a Jupiter-mass object would have $R_h \simeq 0.7$ AU.

In the event of a close encounter, the embryo will tend to scatter the planetesimal to a smaller or larger orbit, exchanging energy and angular momentum. Consequently, the embryo will respond by moving in the opposite direction of the planetesimal, albeit by a much smaller amount. Since an embryo is surrounded by a swarm of planetesimals, it will scatter numerous planetesimals as it moves along its orbit. Furthermore, if the probability of scattering a planetesimal inwards were the same as scattering outwards, there will be no net change of the embryo's orbit. However, since the timescale for a scattering encounter is slightly shorter inside the planet's orbit, it will preferentially scatter planetesimals from inside its orbit to outside its orbit. Consequently, the embryo will experience a net inward drift, and this inward migration will continue so long as there is sufficient material for it to scatter (Fernandez and Ip, 1984; Malhotra, 1993; Gomes et al., 2004). This migration is studied in detail by Kirsh (2007) and Kirsh et al. (2009) in gas-free disks, and we briefly summarize their work here.

In their study Kirsh et al. (2009) noted that if a swarm of planetesimals were scattered by a much more massive embryo, it could lead to a net exchange of angular momentum that would induce the embryo to migrate. The rate an embryo's orbital distance will drift due to planetesimal scattering is given by Kirsh et al. (2009):

$$\left.\frac{\dot a}{a}\right|_{\rm sca} \simeq -\frac{2}{P_{\rm orb}}\left(\frac{M_{\rm disk}}{M_\odot}\right)\left[1+\frac{1}{5}\left(\frac{M_{\rm em}}{M_{\rm enc}}\right)^3\right]^{-1} \tag{2}$$

where $P_{\rm orb}$ is the embryo's orbital period at $a_{\rm em}$, while $M_{\rm disk} \equiv \Sigma_{\rm solid}(a_{\rm em})\pi a_{\rm em}^2$ is the local mass of the disk, where $\Sigma_{\rm solid}(a_{\rm em})$ is the local surface density of the solid material in the disk and $M_\odot$ is the solar mass. This rate will be independent of $M_{\rm em}$ provided $M_{\rm em} \ll M_{\rm enc}$ where $M_{\rm enc} \simeq 5\xi_h M_{\rm disk}$ is the mass in the embryo's encounter region, and $\xi_h = R_h/a_{\rm em} \equiv (M_{\rm em}/3M_\star)^{1/3} = 10^{-2}\,(M_{\rm em}/M_\oplus)^{1/3}$ is the Hill factor.