Icarus 232 (2014) 118–132

Contents lists available at ScienceDirect

Icarus

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

Planetesimal-driven migration of terrestrial planet embryos ☆

David A. Minton [a,*], Harold F. Levison [b]

[a] Purdue University, Department of Earth, Atmospheric, & Planetary Sciences, 550 Stadium Mall Drive, West Lafayette, IN 47907, United States
[b] Southwest Research Institute and NASA Lunar Science Institute, 1050 Walnut St. Suite 300, Boulder, CO 80302, United States

ARTICLE INFO

Article history:
Received 7 February 2012
Revised 23 December 2013
Accepted 1 January 2014
Available online 13 January 2014

Keywords:
Origin, Solar System
Planetary formation
Planetesimals

ABSTRACT

We develop a model for planetesimal-driven migration (PDM) in the context of rocky planetary embryos in the terrestrial planet region during the runaway and oligarchic growth phases of inner planet formation. We develop this model by first showing that there are five necessary and sufficient criteria that must be simultaneously satisfied in order for a rocky inner Solar System embryo to migrate via PDM. To investigate which embryos within a given disk satisfy the five criteria, we have developed a Monte Carlo planetesimal merger code that simulates the growth of embryos from a planetesimal disk with nebular gas. The results of our Monte Carlo planetesimal merger code suggest that, for typical values of the minimum mass solar nebula for the inner Solar System, an average of 0.2 embryos capable of PDM emerge over the lifetime of the disk. Many disks in our simulations produce no migration candidates, but some produced as many as 3. The number of embryos that experience PDM in a disk increases with increasing disk mass and decreasing il planetesimal mass, although we were not able to simulate disks where the average initial planetesimal size was smaller than 50 km. For disks 4× more massive than the standard minimum mass solar nebula, we estimate that an average of 1.5 embryos capable of PDM emerge, with some producing as many as 7.

1. Introduction

A phenomenon called planetesimal-driven migration (PDM) has been studied in the context of the evolution of giant planet orbits (Fernandez and Ip, 1984; Malhotra, 1993; Levison et al., 2007) and giant planet cores (Levison et al., 2010). PDM arises from the asymmetric scattering by a large body embedded in a disk of planetesimals (Kirsh et al., 2009). When a large body preferentially scatters planetesimals either inward (toward the Sun) or outward (away from the Sun), net orbital angular momentum is transferred between the disk and the large body, causing a drift in the large body's semimajor axis. Simulations of rocky planet formation in the inner Solar System have not included PDM, because, as we will show, these simulations have not had the resolution necessary to resolve this process.

Unfortunately, as we discuss in more detail below, we cannot yet perform a single end-to-end calculation of terrestrial planet formation that captures the important physical processes accurately enough. We designed a multi-stepped series of calculations that are intended to focus on evaluating whether PDM should be considered an important process in terrestrial planet formation, rather than to perform accurate terrestrial planet formation simulations. In particular, our goal is to determine the conditions that lead to PDM of terrestrial embryos, and show how the growth history of embryos is altered for those objects that undergo PDM.

Using N-body simulations, we identify five criteria that must be simultaneously met in order for PDM to take place, which are each described in detail in Section 2.3. In Section 3 we use a newly developed Monte Carlo code called *GAME* (Growth And Migration of Embryos) to model planetary accretion through the runaway and oligarchic regimes. We use results of *GAME*, coupled with our migration criteria, to show when and where PDM can occur for a variety of plausible models for the inner Solar System planetesimal disk. As we will show in more detail, PDM allows a small number of embryos to become highly mobile in the disk. This mobility may alter the assumption about how embryos and planetesimals are distributed in the terrestrial planet disk during the start of late-stage accretion.

1.1. Summary of planet formation models

We briefly summarize the "standard" methods used to study the formation of terrestrial planets in order to understand why PDM has not been seen in previous work. The bodies of the inner Solar System are thought to have formed in a hierarchical process that began with dust grains entrained within a gaseous disk and

---

* Corresponding author.
E-mail address: daminton@purdue.edu (D.A. Minton).

0019-1035/$ - see front matter © 2014 The Authors. Published by Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.icarus.2014.01.001

ended with Mercury, Venus, the Earth–Moon system, Mars, and the main asteroid belt. This process is difficult to study in its entirety because of the vast range of mass, time, and distance scales involved. Terrestrial planet formation is therefore broken up into several discrete stages.

Early on, the largest bodies in the swarm tend to grow fastest, in a process known as runaway growth, on a timescale of 10^4—10^6 y (Greenberg et al., 1978; Wetherill, 1980, 1990; Lissauer and Stewart, 1993; Wetherill and Stewart, 1989, 1993; Kokubo and Ida, 1996; Weidenschilling et al., 1997). When the largest bodies in the swarm grow large enough to dominate the dynamics of the disk through gravitational scattering, their growth slows down, and runaway growth transitions to oligarchic growth (Kokubo and Ida, 1998, 2000, 2002; Kominami and Ida, 2002; Thommes et al., 2003; Leinhardt and Richardson, 2005; Leinhardt et al., 2009; Levison et al., 2010).

The end result of this classic model of embryo growth is an "oligarchy" of many large embryos (10^{-2} to 10^{-1} $\mathrm{M}_\oplus$, where $1\ \mathrm{M}_\oplus = 6 \times 10^{27}$ g), separated in semimajor axis by $\sim 10R_H$, where $R_H = a(M/3\ \mathrm{M}_\odot)^{1/3}$ is Hill's radius, and containing half the mass of solids in the disk (Kokubo and Ida, 1998). The process of planet-formation then transitions to late-stage accretion, when over a period of several 10^7 years, growth of bodies is dominated by chaotic embryo–embryo mergers (Wetherill, 1985, 1990, 1992; Agnor et al., 1999; Chambers, 2001; Kominami and Ida, 2002; Nagasawa et al., 2005; O'Brien et al., 2006; Kenyon and Bromley, 2006; Raymond et al., 2005, 2006, 2009).

The study of terrestrial planet formation has advanced considerably in the past decade with improvements in computing power (e.g., O'Brien et al., 2006; Raymond et al., 2009). Simulations of the late-stage accretion generally result in terrestrial planet systems that broadly resemble our own. For instance, simulations can produce systems that match the observed orbital excitation of the terrestrial planets, as measured by their angular momentum deficit (AMD), in contrast with the previous generation of simulations (c.f. Brasser, 2013). Nevertheless, many important problems in terrestrial planet formation remain unsolved. In particular, the small sizes of both Mercury and Mars are difficult to produce in conventional models of terrestrial planet formation (Wetherill, 1991; Chambers, 2001; Raymond et al., 2009; Morishima et al., 2010).

Various researchers have addressed these specific discrepancies between terrestrial planet formation model outcomes and observations. However, the majority of simulations of the late-stage accretion take as their initial conditions the system of embryos and planetesimals that result from the "classic" runaway-to-oligarchic growth stage, which assumes that embryos grow by accreting mass from their local feeding zone. These earlier stages are modeled either using analytical or semi-analytical techniques (Weidenschilling, 1977a; Greenberg et al., 1978; Wetherill and Stewart, 1989), hybrid Monte Carlo and N-body codes (Spaute et al., 1991; Weidenschilling et al., 1997; Bromley and Kenyon, 2006; Kenyon and Bromley, 2006), or very limited fully N-body simulations (Kokubo and Ida, 1996, 1998, 2000). The results of a study in these early stages have typically lead to the initial conditions used in studies of late stage accretion. Here we show how the addition of PDM could potentially alter the distribution of mass at the start of late stage accretion.

There are two main limitations in the earlier simulations that have prevented PDM from occurring. The first limitation is one of resolution. In Section 2.2 we show that migration occurs when an embryo is $\gtrsim 100\times$ the mass of a typical local background planetesimal. When the mass ratio between embryos and disk planetesimals is less than $\sim$100, embryo motion is stochastic, and embryos random walk in semimajor axis. When the mass ratio is above this limit, embryo motion is relatively smooth and monotonic. In a terrestrial planet simulation, this requires a large number of simulated planetesimals in order to properly model the full disk, and typically simulations involving embryos embedded in planetesimal disks use planetesimals larger than 1/40 the mass of the embryos (O'Brien et al., 2006; Raymond et al., 2009).

The second limitation involves assumptions about how embryos are initially distributed in the protoplanetary disk. An embryo will only migrate if it is able to travel through an embryo-free zone of the disk, a criterion that we will quantify in Section 2.3.5. This requires that embryos form in some places in the disk before others—a situation that arises in simulations of runaway and oligarchic growth (Weidenschilling et al., 1997; Thommes et al., 2003). However, for reasons described above, N-body models of late-stage accretion take as their initial conditions a situation in which all embryos throughout the terrestrial planet region have already formed throughout the disk (Chambers and Wetherill, 1998; Agnor et al., 1999; Chambers, 2001; O'Brien et al., 2006; Raymond et al., 2009).

2. Quantifying the planetesimal-driven migration process

Planetesimal-driven migration can be understood in the following way. A close encounter between a single small planetesimal and much larger body (such as a planet or planetary embryo) can either increase or decrease the orbital angular momentum of the planetesimal and inversely that of the larger body. Whether the planetesimal experiences an increase or a decrease in orbital angular momentum depends on details of the encounter. Once a planetesimal begins to scatter off the large body, it will tend to continue scattering. Scattering will only halt if (1) the planetesimal impacts the large body, (2) it is ejected from the Solar System, (3) drag forces remove it from the region of influence of the large body, (4) it scatters off another nearby large body, or (5) the large body drifts a significant distance in semimajor axis between scatterings, thereby moving beyond the reach of the particle.

The large body tries to set up a steady state situation where it is scattering an equal mass of planetesimals inward as outward. Any imbalance in the mass of planetesimals that are scattering inwards compared to the mass of planetesimals that are scattering outwards will cause a net angular momentum transfer between the planetesimal disk and the large body. This results in a drift of the large body's semimajor axis, either inwards or outwards in response. Several factors can influence the direction of migration. Kirsh et al. (2009) showed that, in the absence of gas, an isolated embryo in a cold planetesimal disk starting from a stationary orbit will tend to migrate inward. However, such an idealized situation likely never occurs in nature. For instance, when two embryos are embedded in a planetesimal disk, they tend to repel each other (Kokubo and Ida, 1995). In addition, migration in either direction is self-sustaining, meaning that once a large body begins migrating in one direction it tends to keep moving in that direction (Kirsh et al., 2009). And so, the outermost embryo of a population will tend to migrate outward, away from its inward neighbors.

The self-sustaining nature of the direction of migration is due in part to the nature of the planetesimal disk on either side of the migrating body. When a large body scatters planetesimals in its neighborhood, the scattering process excites planetesimals and increases their eccentricity in a specific way. The Tisserand parameters of the planetesimals, defined relative to the large body's semimajor axis a_p as $T_p = a_p/a + 2\sqrt{a/ap(1-e^2)}\cos i$, is approximately conserved through scatting, so that after scattering planetesimals' new a, e, and i are constrained to a surface. On a plot of a versus e, these surfaces have the appearance of two "tails" that point out and away from the large body. If the large body is migrating (either inward or outward), then it moves away from the whichever tail is on its trailing side. Therefore the migrating body