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Reinventing planet formation: the important roles of planetesimal-driven migration and collisional grinding during embryo growth.

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Abstract

The addition of planetesimal-driven migration (PDM) and collisional grinding radically alters the nature of oligarchic growth and late-stage accretion in the formation of the terrestrial planets. We show here four criteria under which PDM can occur in a rocky planetesimal disk.

1. Introduction

Planet formation is difficult to study in its entirety because of the vast range of mass, time, and distance scales involved. This difficulty has lead to some possibly erroneous assumptions about planet formation. In particular, a commonly used template for the initial conditions of late-stage accretion simulations of the inner solar system is to place roughly half the mass of solids in 10^{-2}–10^{-1} $\mathrm{M}_\oplus$ embryos spaced 5–10 $\mathrm{R_H}$ apart and the other half in much smaller planetesimals [1–3]. This template is based on the oligarchic growth model, in which the largest bodies in a swarm of planetesimals grow to dominate their local dynamical environment and becomes isolated from neighboring oligarchs [4]. We show here that this template may be altered altered by the addition of PDM and collisional grinding.

2. Four criteria for initiating PDM

PDM occurs when a large body, such as a planetary embryo, embedded in a planetesimal disk scatters the planetesimals asymmetrically [5–7]. Asymmetric scattering means that the mass of planetesimals being scattered toward the Sun does not balance that being scattered away, and the embryo experiences a net change in angular momentum. This process is self-sustaining, and once migration initiates in one direction it tends to continue in that direction [7]. Here we describe the four criteria that must be satisfied in order for PDM to occur in a planetesimal disk.

2.1. The mass ratio criterion

Migration wills tall if the ratio $M_p/M_{enc} \gtrsim 3$, where M_p is the mass of the embryo and M_{enc} is the total mass of planetesimals being scattered [7]. The encounter mass can be expressed as $M_{enc} \approx 5\left(M_p/3M_\odot\right)^{1/3}\pi\Sigma_m a_p^2$, where Σ_m is the surface mass density of the local planetesimal disk. The mass ratio criterion can be expressed in terms of a stopping mass, $M_{stop} \approx \left[15\pi\left(3M_\odot\right)^{-1/3}\Sigma_m a_p^2\right]^{3/2}$.

If the embryo grows larger than this mass, it will be unable to experience PDM. For the inner solar system, this value is 10^{-2}–10^{-3} $\mathrm{M}_\oplus$ for a standard Minimum Mass Solar Nebula (MMSN) disk model with $\Sigma_m(1\ \mathrm{AU}) = 8\ \mathrm{gm\ cm^{-2}}$ [8], and scales directly with the disk mass.

2.2. The growth timescale criterion

In order for PDM to occur, an embryo must be able to migrate through embryo-free zones of the disk before new embryos have a chance to form. This can be understood by comparing the timescale for migration, τ_{mig}, with the timescale for the outwardly propagating embryo growth front, τ_{grow}. The timescale for migration is $\tau_{mig} = a/|\dot{a}_{fid}|$, where the fiducial migration rate is [7]:

$$\dot{a}_{fid} \approx \frac{1}{2}\frac{a_p}{T_p}\frac{4\pi\Sigma_m a_p^2}{M_\odot}, \tag{1}$$

where T_p is the local Keplerian orbital period.

The embryo growth timescale, τ_{grow}, is somewhat more complicated. The embryo growth timescale is a function of semimajor axis, and at any given time a semimajor axis exists where the largest object mass is some value, which we call M_{olig}. The rate of propagation of this embryo growth front is $\dot{a}_{grow} = da/dT_{olig}$, where:

$$T_{olig} = \frac{3e_m^2 a^{1/2}}{C\Sigma_m}\left(M_0^{-1/3} - M_{olig}^{-1/3}\right), \qquad (2)$$

where e_m is the eccentricity of the planetesimal disk, and C is a constant [9].

For reasonable disk masses (1–$10\times$MMSN), we find that the growth timescale criterion is met beyond 0.6–1 AU. Embryos will only be able to migrate after they first form beyond this location.

2.3. The disk eccentricity criterion

PDM can only occur when the disk eccentricity relative to the Hill eccentricity of the embryo is $\lesssim 5$ [7]. The disk eccentricity is a complex function in semimajor axis and time, and depends greatly on models of the gas disk and collisional evolution in the disk. In general, we find that the disk eccentricity criterion is more easily met for massive disks than less massive ones, and that the location at which the criterion is met changes as a function of time.

2.4. The crowded criterion

The crowded criterion requires that embryos have room to migrate away from other embryos. In order for migration to sustain itself, an embryo must be able to grow enough along its migration path that when it meets a neighboring embryo, it is at least $10\times$ the neighbor's mass. We find that rates of growth for embryos are quite high during migration:

$$\dot{M}_{mig} \approx \frac{\pi}{10}\dot{a}\Sigma_m a. \qquad (3)$$

For 10^{-2} $\mathrm{M}_\oplus$ embryos at 1 AU, this growth rate is about two orders of magnitude faster than the runaway growth rate. Even with the very large migration growth rate, the standard oligarhic growth spacing of 10 $\mathrm{R_H}$ this is too crowded for migration to occur.

However, we find that including collisional evolution during the transition from runaway to oligarchic growth dramatically changes the picture. We performed a simulation with a new code called LIPAD of a $2\times$MMSN planetesimal disk from 0.7–1.5 AU in Figure 1. LIPAD stands for Lagrangian Integrator for Planetary Accretion and Dynamics. It can follow the dynamical/collisional/accretional evolution of a large number of km-sized planetesimals through the entire growth process to become planets.We find that, rather than tightly packed embryos as in standard oligarchic growth models, LIPAD produces very widely spaced embryos, which easily satisfy the crowded criterion.

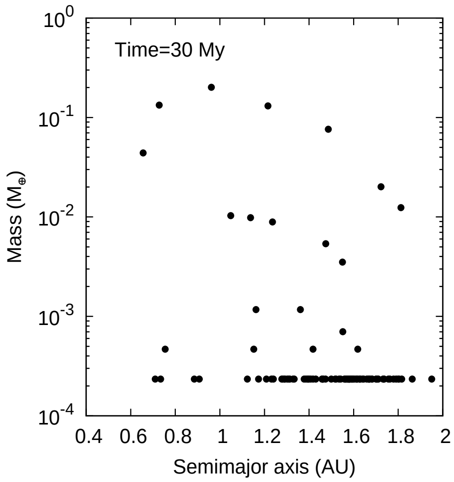

Figure 1: A $2\times$MMSN disk collisionally grinds itself very rapidly in this simulation result using our planet formation code, LIPAD.

3. Summary and Conclusions

The addition of PDM and collisional evolution of planetesimal disk greatly alters the character of oligarchic growth. This will require a reevaluation of the initial conditions used in late-stage accretion simulations.

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4 References

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