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Planetesimal-Driven Migration Verses Type I: Rethinking Giant Planet Formation.

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Abstract

In Ref. [1, 2], we showed that planetesimal-driven migration [3] overpowers that of Type I [4, 5] for planetary embryos with masses less than $\sim 8\,M_\oplus$. Here we present new N-body simulations that investigates how this result affects the migration and growth of a system of giant planet cores. Preliminary results suggest a heretofore unknown and unexpected mechanism for building all four giant planets.

1. Introduction

It has been known for many years that the gravitational interaction between the growing planets and the gas nebula [6, 7, 4] generally leads to inward migration. Planet-disk interactions are typically broken down into three different regimes. Only the first, known as "Type I" migration [4], is relevant to the problem of interest here, namely giant planet core formation, because the others require that the planet be massive enough to significantly perturb the radial surface density profile of the gas disk.

During Type I migration, a body orbiting in a gas disk experiences a repulsive torque from waves that it generates at the locations of both its inner and outer Lindblad resonances [6]; for typical model disks, the outer torques are stronger and inward migration results [7]. The timescale for a body to migrate all the way in to the star is

$$t_{\rm Type\,I} \sim 8\times10^5 \left(\frac{M}{1\,M_\oplus}\right)^{-1} \left(\frac{\Sigma_{\rm gas}}{\Sigma_{\rm MMSN}}\right)^{-1} \left(\frac{a}{5{\rm AU}}\right) {\rm yr} \quad (1)$$

[5], where $\Sigma_{\rm gas}$ is the surface density of the nebula, and $\Sigma_{\rm MMSN}$ that of the minimum-mass solar nebula [8]. The timescale for dispersion-dominated oligarchic growth of a core-sized body at ~ 5 AU is substantially larger than this citeTDL03. If a giant planet core does not grow faster than the time it takes to plunge into the central star, how can any ever form?

In Ref. [1], we discovered a new way to mitigate the effects of Type I migration. In addition to planet-disk interactions, gravitational interactions between a planet and a disk of planetesimals can also lead to large-scale migration [3]. Indeed, both types of migration, Type I and planetesimal-driven, should be active during core formation. However, the effects of planetesimal-driven migration have largely been ignored when gas is present because it was believed that Type I migration would dominate. After all, there was a lot more gas than planetesimals in the disk. We were surprised to realize that Type I did not overwhelm planetesimal-driven migration. A comparison between the Type I migration rate, Eq. 1, to one that describes planetesimal-driven migration by [10],

$$t_{\rm p} \sim 10^5 \left(\frac{\Sigma_{\rm m}}{\Sigma_{\rm m,MMSN}}\right)^{-1} \left(\frac{a}{5{\rm AU}}\right) {\rm yr}, \quad (2)$$

where $\Sigma_{\rm m,MMSN}$ is the planetesimal surface density for the MMSN with solar metallicity, suggests that for embryos with masses less than $\sim 8\,M_\oplus$, planetesimal-driven migration should dominate in solar metallicity disks, as long as the disk surface density is large enough to support planetesimal-driven migration (i.e. planet's mass is less than that of the planetesimals within a few Hill radii).

In [2] we studied the relationship between Type I and planetesimal-driven migration. In particular, we studied the behavior of a single Earth-mass planet embedded in a disk consisting of both gas and planetesimals. All the planetesimals suffered the effects of aerodynamic drag and were assumed to be the same size. We found that in all cases, planetesimal-driven migration dominated (cf. Figure 1). The planet can migrate in either direction depending, in the single planet case, on the size of the planetesimals. There are three modes: 1) For large planetesimals, gas drag does not matter. The planet migrates inward due to a subtle asymmetry in the scattering dynamics. 2) Small objects get trapped in MMRs and push the planet in.

3) For intermediate size planetesimals, the planet migrates outward due to the fact that the gas density is higher closer to the Sun, and thus aerodynamic drag is stronger. So, when the embryo scatters planetesimals inward, they are more likely to become removed from the planet-crossing region than if they were scattered outward. Note that in almost all cases the planet migrates faster than Type I would predict.

We also found that if we were to push an embryo outward for a short distance, it would continue to migrate outward for a wide range of planetesimal sizes. This is because the migration itself sets up a distribution in the planetesimals that promotes migration in the same direction — it is self sustaining. Thus, we expect that in systems with more than one planet, the direction of migration will strongly depend on the behavior of neighboring planets.

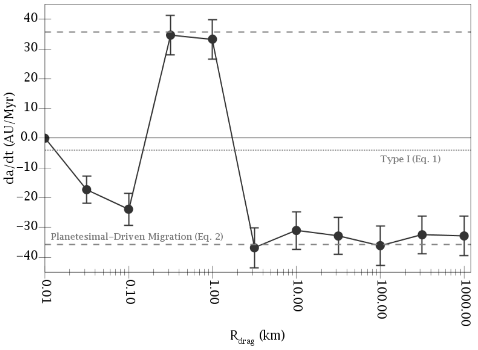

Figure 1: The migration rate of an Earth-mass planet in response to a combination of Type I and planetesimal-driven migration as a function of the radius of the planetesimals. The planetesimals suffered aerodynamic drag. The dotted and dashed lines show the predicted migration rate for Type I (Eq. 1) and planetesimal-driven (Eq. 2) migration, respectively.

2. Calculations & Results

We are performing a series of N-body simulations to test Ref. [2]'s suggestion that the outermost members of a population of planetary embryos will experience a burst of outward migration even when Type I migration is accurately accounted for. Building on the results of Ref. [1], we expect that this migration will also lead to very large accretion rates, thereby building the giant planet cores before the solar nebula disperses. Indeed, preliminary results suggest a heretofore unknown and unexpected mechanism for building all four giant planets. This new model will be discussed.

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