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Dynamical interactions and planetary growth in a protoplanetary disk

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Abstract

Earth- to Neptune-mass planets launch spiral density waves in gaseous protoplanetary disks and undergo type 1 migration. In isothermal disks, type 1 migration is inward and the migration timescale is inversely proportional to the planet mass. In radiative disks migration can be directed inward or outward, depending on the planet's mass and the disk's physical properties. For a given planet mass, there exist locations within the disk where the migration is convergent. We present results of N-body simulations of systems of planetary embryos of a few Earth masses embedded in radiative disks. We concentrate on the collective behavior of the system of embryos and their collisional growth.

1. Introduction

A major problem in planet formation is the growth of giant planet cores. Convergence zones in protoplanetary disks represent one potential solution to this problem. A planet of a few $M_\oplus$ in a radiatively-inefficient region of a disk migrates outward due to a strong corotation torque. The migration slows as the planet enters regions of the disk that cool more efficiently (i.e., have smaller optical depth), and stops when the planet reaches a region in the disk where the total torque is zero [1]. A planet of the same mass that formed farther out in the disk migrates inward to this same orbital distance. These convergence zones can thus concentrate mass within the disk [2].

2. Mass-independent convergence zone

As a first step in the understanding of convergence zone, we study a fake mass-independant convergence zone to understand the influence of this specific zone of the disk onto planetary growth.

The formation of resonant chains between embryos plays an important role in our study. These can either stop planetary growth by trapping a reasonable amount of embryos into stable resonance that prevent them to collide, or when the number of embryos is sufficiently high enhance collision rates between bodies due to eccentricity pumping. In the vicinity of the convergence zone there is a competition between the torque exerted by the disk, that tends to push embryos toward the zero-torque zone, and the resonances that tend to prevent embryos to collide with each other.

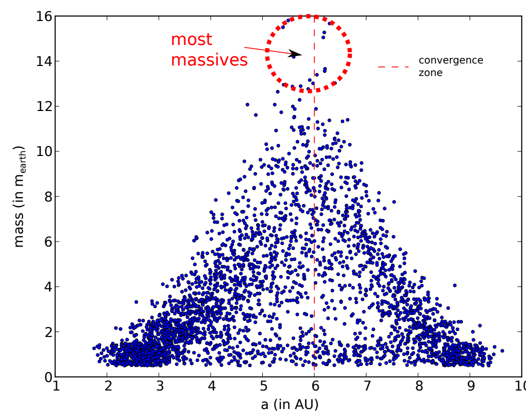

Figure 1: With respect to the convergence zone located at 6AU are showed all the surviving planets in 200 simulations (50 planets of $1m_\oplus$ each at the beginning).

By increasing the number of embryos in the resonant chain, the system becomes strongly compressed. Consequently, the average distance between embryos tends to decrease, while the eccentricity of each embryos increase, to such a point that the resonant chain is no longer stable and collisions can occurs. This decreases the total number of embryos in the system while the average separation between embryos tends to increase.

As we can see on Fig. 1, the most massives embryos formed are located close to the convergence zone.

3. Application to a more realistic disk

We now use the mercury code [3], which we modified by adding the migration torque formulae given by [1]. In our simulations, the surface density profile decreases as a power-law and the temperature profile is computed by assuming that only viscous heating operates inside the disk. Radiative cooling is computed using the opacity table in [4].

For different masses and position in the disk, Fig. 2 displays the adimensioned torque profile. The figure can be read as follows : An iso mass (constant y) gives the torque felt by a planet for various positions in the disk. The black line represents the zero-torque zone in the disk. It reveals that we have two convergence zones. One close from the star, fairly mass independant, due to the opacity transition and another one, mass-dependant, in the outer part of the disk.

The figure Fig. 3 gives the evolution of 50 embryos of $1\mathrm{m}_\oplus$ over 10 millions years. Each time a collision occurs, the merged embryos jump into another regime of the torque diagram, where the zero-torque zones are located differently.

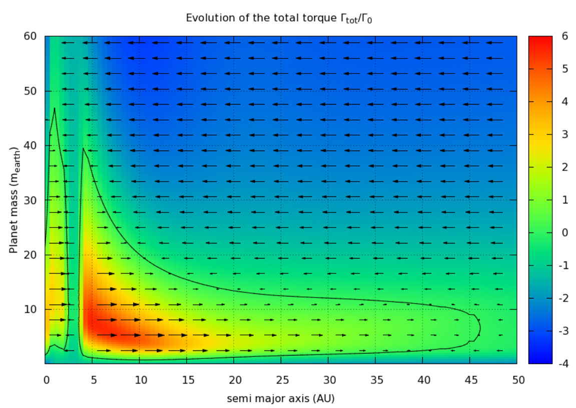

Figure 2: This diagram represent the torque felt by a planet of a given mass and position in the disk. The arrows shows the direction of migration, and the black line show the zero-torque zone.

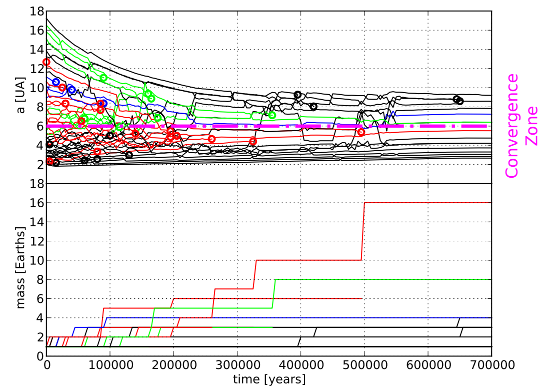

Figure 3: This diagram represent the evolution of 50 planets during 10 millions years. The circles represent collisions, the colours are linked to the final planet in which the embryos finish. Thus, each embryos marked as red will end in the most massive $16\mathrm{m}_\oplus$ embryo.

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