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Forming Planetary Cores in a Turbulent Non-Isothermal Disk

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Abstract

Non-Isothermal disks have been shown to have regions where the net torque on a planet is positive, leading to outward migration of the planet. When a region with negative torque is directly exterior to this, planets in the inner region migrate outwards and planets in the outer region migrate inwards, converging where the torque is zero. We incorporate the torques from an evolving non-isothermal disk into an N-body simulation, and find that the bodies do converge to the zero torque region, but effects of neighbouring planets prevents the planets from merging. Though N-body interactions prevent complete merging to form one core, the addition of a weak stochastic force to simulate turbulence in the disk allows for orbit crossings and mergers near the convergence zone. In this way, it is possible to move from the sub-Earth mass regime into the 10 Earth mass planetary core regime in 2-3 million years.

1. Introduction

The formation of gas giant planets via core accretion requires that planetary embryos grow into planetary cores via collisions [7]. These cores must form early enough in the lifetime of the gas disk that enough gas is present to accrete onto the planetary core to form a giant planet. A turbulent disk leads to planetary embryos undergoing a random walk, thus avoiding uninhibited type I inward migration, while also leading to collisions between embryos [2].

Paardekooper and Mellema [5] showed that a non-isothermal disk can stop inward migration and even lead to outward migration in regions of high opacity. Lyra et al. [1] built on this finding, investigating how single planets migrate in an evolving non-isothermal disk, incorporating photoevaporation and stellar wind. They found that bodies from a wide range of initial radii migrate towards the zero-torque region in the disk. Embryos from a large region of the disk could thus migrate to the convergence zone and merge to form planetary cores.

Our simulations incorporate this evolving non-isothermal disk into an N-body solver. The torque from the gas onto a planet is determined by the local temperature and density gradient, which is found by reading in the temperature and density profiles of the disk as it evolves. Preliminary results show that embryos do migrate towards the zero-torque region, but interactions with neighboring embryos— resembling resonance— prevent orbit crossing and merging.

Turbulence is modeled into the simulation by the addition of a Markov process to generate stochastic forces for each planet [7]. This stochastic force breaks the resonances and leads to interactions and mergers between planets. It does not, though, lead to the creation of one large core in our preliminary simulations, but multiple medium mass bodies (3-6 Earth mass) that appear to be trapped in some resonance.

2. The Model

2.1 Non-Isothermal Disk

We ignore the back reaction on the planet onto the disk. This allows us to simulate the evolution of the disk prior to the n-body simulations. The gas evolution is explained in Lyra [1]. The density and temperature profiles are printed out on 1000-year time-steps, to be read into the n-body simulation. The torque from an adiabatic disk onto a planet takes the form [4]:

$$\gamma \Gamma_{ad} / \Gamma_0 = -0.85 - \alpha - 1.75\beta + 7.9\zeta / \gamma \quad (1)$$

where

$$\alpha = -\frac{\partial \ln \Sigma}{\partial \ln r}; \quad \beta = -\frac{\partial \ln T}{\partial \ln r}; \quad \zeta = \beta - (\gamma - 1)\alpha \quad (2)$$

$$\Gamma_0 = (q/h)^2 \Sigma_p r_p^4 \Omega_p^2 \quad (3)$$

The torque on a planet is calculated at each step of the integration by looking up the temperature and density profiles for the planet's location in the two nearest profile printouts from the disk simulation and linearly interpolating to the current time in the simulation.

2.2 Turbulence

Turbulence is treated in the manner of Ogihara et al, [2] by having the stochastic force acting on a planet be the gradient of a potential. The potential is formed by summing over 50 randomly selected modes:

$$F_{tub} = -\Gamma \nabla \Phi$$
$$\Phi = \gamma r^2 \Omega^2 \sum_{i=1}^{50} \Lambda_{c,m} \quad (4)$$

where Γ and $\Lambda_{c,m}$ are defined in Ogihara [2].

We have also used a simpler model for the stochastic force that treated it as a Markov process [7] that had an autocorrelation function and distribution of torques similar to those seen in local MHD simulations [3]. This did make the planets' semi-major axes undergo random walks, but the oversimplification led to there being no correlation between the force acting on two nearby planets. Thus the turbulent potential model will be used in upcoming runs.

2.3 N-Body Code

We use a Bulirsch Stoer integrator with a $1M_{\odot}$ central body and 5-20 planet embryos, separated by a set number of mutual Hill radii. The code is modified to add in accelerations from the stochastic force and the gas torque before applying the Bulirsh Stoer algorithm. Since the gas profiles are generated beforehand, the integrator can relatively quickly evolve a system through a 10 million year lifetime.

3. Preliminary Results

As expected, planets do migrate towards the convergence zone on a timescale determined by the mass of the planet. If turbulence is not added, simulations with a small number of planets fail to have any mergers or migrate completely to the central stable orbit. Adding turbulence, planets do collide and merge, and the more massive resulting bodies experience larger accelerations from the disk, so that the most massive body settles nearest the convergence zone, and a smaller number of bodies are trapped in apparent resonances further outside of the convergence zone.

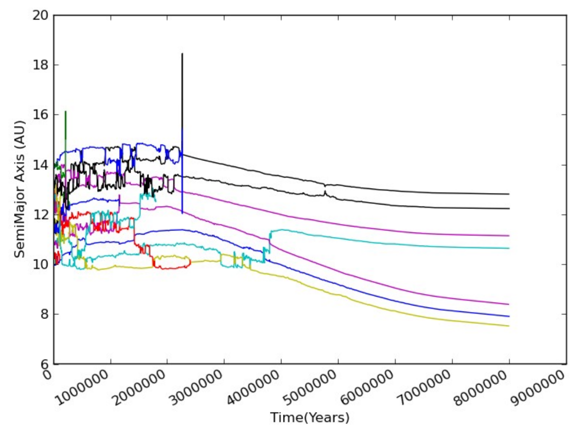

Fig 1. A simulation initially with 16 Earth-mass bodies that merge into 7, the 4 lightest of which are scattered away from the convergence zone to large radii. The more massive bodies migrate inwards at the viscous timescale. Sharp peaks in the semi-major axis result from converting from position an velocity to orbital elements when two bodies are orbiting one another.

References

[1] Lyra, W., Paardekooper, S.-J. & Mac Low, M.-M. Orbital Migration of Low-mass Planets in Evolutionary Radiative Models: Avoiding Catastrophic Infall. *The Astrophysical Journal* **715**, L68-L73 (2010).

[2] Nelson, R.P. & Papaloizou, J.C.B. The interaction of giant planets with a disc with MHD turbulence - IV. Migration rates of embedded protoplanets. *Monthly Notices of the Royal Astronomical Society* **350**, 849-864 (2004).

[3] Ogihara, M., Ida, S. & Morbidelli, A. Accretion of terrestrial planets from oligarchs in a turbulent disk. *Icarus* **188**, 522-534 (2007).

[4] Oishi, J.S., Mac Low, M.-M. & Menou, K. Turbulent Torques on Protoplanets in a Dead Zone. *The Astrophysical Journal* **670**, 805-819 (2007).

[5] Paardekooper, S.-J., Baruteau, C., Crida, A. & Kley, W. A torque formula for non-isothermal type I planetary migration - I. Unsaturated horseshoe drag. *Monthly Notices of the Royal Astronomical Society* **401**, 1950-1964 (2010).

[6] Paardekooper, S.-J. & Mellema, G. Halting type I planet migration in non-isothermal disks. *Astronomy and Astrophysics* **459**, L17-L20 (2006).

[7] Rein, H. & Papaloizou, J.C.B. On the evolution of mean motion resonances through stochastic forcing: fast and slow libration modes and the origin of HD 128311. *Astronomy and Astrophysics* **497**, 595-609 (2009).

[8] Safronov, V.S. *Evolution of the protoplanetary cloud and formation of the earth and planets.* (1972).