Planetesimal formation by turbulent concentration.

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Planets originate from a circumstellar protoplanetary disk made up of the remains of the stellar accretion disk. While most of this material is made up of Hydrogen and Helium gas (99% for our Solar System), some of the material (1%) is made up of solid dust grains embedded in this gas-rich environment.

The current model of planet formation has these dust grains coalescing to form bodies roughly 1-1000 km in size, planetesimals. Since larger objects have a bigger crossection of interaction, they tend to grow even faster, leading to a runaway growth stage. Eventually, a small number of oligarchs appear, planetesimals that are large enough their local dynamical environments via gravity. This oligarchic growth stage results in planetary embryos. This stage ends when the embryo contains nearly half the solid material in its region. Planetary embryos that reach a mass larger than $\tilde{1}0$ Earth masses are able to efficiently accrete gas from the disk, forming gas giants.

While the current model is able to explain the latter stage of planet-formation (after planetesimals are formed), the theory behind the formation of 1-1000 km sized planetesimals from micrometer sized dust grains is still poorly understood. Understanding the evolution of dust-grains to planetesimals is vital, because it provides a clearer picture of the conditions of the protoplanetary disk after planetesimal formation.

Initially, it was thought that planetesimals could form through gravitational instabilities. Solid material would sediment to the mid-plane of the disk, creating enough density for a gravitational collapse. This was shown to be unfeasible, as gravitational collapse requires large surface densities and that the particles have small relative velocities. These conditions could possible in a disk that has zero turbulence (laminar disk). However, even low levels of turbulence prevents particles from settling in the mid-plane of the disk. Furthermore, the presence of particles themselves in the mid-plane generates turbulence. The particle layer tends to orbit the star at Keplerian velocities, while the gas-rich layer orbits slightly slower due to an outward pressure gradient. This velocity sheer gives rise to turbulence.

Another theory that gained some favor was the idea of pairwise sticking. Planetesimals could form through dust grain collisions. Small dust grains could stick to one another if they collided at low velocities and become bound through electrostatic forces (Van der Waals force). These dust grains continually collide and merge until they become large enough such that they can acquire more material gravitationally. However, once these dust-grains reach centimeter-to-meter sizes, they begin to experience rapid-inward drift due to gas drag. Furthermore, turbulence leads to large collision speeds, frustrating growth as these grains can potentially fragment. As planet formation necessitates planetesimals larger than 1 m in size, some other process is needed to overcome this meter-size barrier.

Chambers (2010a) proposes a mechanism for planetesimal formation in a turbulent disk from millimeter sized dust-grains. Particles of millimeter size experience drag forces that allow them to have dynamical timescales comparable to the smallest turbulent eddies at the Kolmogorov scale (the scale at which turbulence disappears in a fluid). Experiments and simulations show that these particles tend to concentrate in low vorticity regions in a turbulent fluid. In a protoplanetary disk, these low vorticity regions allow particle concentrations to become sufficiently high such that gravitationally bound clumps of particles can form. These gravitationally bound clumps can then collapse to form planetesimals. The obvious advantage of the model of turbulent concentration is that it uses turbulence as a catalyst rather than an inhibitor for planetesimal growth. Its strength lies in the fact that turbulence is a common feature in protoplanetary disks.

In his paper, Chambers (2010a) uses a cascade model (Hogan & Cuzzi 2007) rather than a numerical hydrodynamical simulation to study turbulent concentration. A cascade model decomposes a generated disk model into the eddies that drive the global turbulence. These eddies hold characteristic properties such as particle concentrations (C) and vorticity (ω) (parameterized by enstrophy $S = \omega^2$) of a region in the disk. The cascade model partitions C and S into lower levels (smaller eddies), cascading down until a Kolmogorov length scale is reached (a scale small enough such that turbulence is dissipated by molecular viscosity.) At such a level, C and S on the disk is examined through the prism of a probability density distribution. This allows for an examination of which particles in the disk are able to form planetesimals. From this, Chambers (2010a) is able to determine planetesimal formation rates, the timescales for planetesimal formation, and the sizes of the resultant planetesimals for a variety of physical disk parameters such as the global particle-to-gas density ratio ($Z = \rho_{part}/\rho_{gas}$), the disk surface density (Σ_{gas}), and the viscosity (α).

Chambers (2010a) puts two constraints on the number of gravitationally bound clumps that are able to collapse in planetesimals. The first constraint is rotational breakup. The centrifugal force on the clump should not exceed the gravitational force. Chambers relates the centrifugal force $\omega^2 R$ acting on the clump to the vorticity ω, equating ω^2 to the Enstrophy. However, Chambers (2010a) makes the assumption that these clumps are spherical. This papers attempts to generalize this assumption to ellipsoidal clumps, to check whether this has any drastic effects on the planetesimal formation rate.

The second of these constraints is the ram-pressure on the clump as it orbits the gaseous disk. Chambers (2010a) compares the ram-pressure to the clump's self-gravity to check whether the clump is stable against ram-pressure stripping. This paper intends to extend Chambers analysis by considering the stability of the self-gravity of ellipsoidal clumps against ram-pressure. Furthermore, this paper intends to determine whether Chamber's assumption of a Stokes drag law (to determine ram-pressure) drastically affects his constraints. By performing a similar analysis but for lower Reynolds numbers (Re)(different drag laws), or higher viscosity, this paper will explore a different parameter space where planetesimals are able to form through turbulent concentration.

References

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