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Numerical approach to planetesimal formation instabilities

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Abstract

In the scenario of planetesimal build up in a solid circumstellar disk with the presence of gas, a problem arises in the centimetre to metre size particles range, at which gas drag would rapidly drive the particles towards the Sun via momentum dissipation. Instead, a phenomenon of gas turbulence may lead to localized regions where the density of solids allows the gravitational instability to occur. The evolution can then proceed in sufficiently small time to accrete kilometre size object, decoupled from the gas. The numerical approach usually employed for investigating this process is incapable, however, of resolving single particles encounters at small scales, as well as monitoring the effective growing process.

We integrate the typical high density regions as issued by the gas evolution by a N-body code developed for self-gravitational systems, that computes gravity and collisions among spherical particles of finite size. Our aim is a study of the small-scale process of planetesimal growth in the regime of gravitational instability.

1. Introduction

The first phase of planetary formation within a circumsolar solid and gas disk is still unclear. In the standard planetary formation models, planetesimal of kilometre size would accrete on each other in successive binary encounters thanks to their reciprocal gravity, with little influence from the gaseous component. The gas plays instead a central role in the previous phase, when particles of centimetre to metre size are strongly interacting with the gas, whose friction tends to subtract them momentum driving them towards the Sun. What recent studies [2] suggest is the important role of the gas turbulent motion, which can be able to increase locally the density of the solid component of some orders of magnitude. As a consequence, gravitational instabilities of the solid component could drive to planetesimal formation on the typical timescale of a free collapse [6], [1]. An intrinsic, practical difficulty in numerical simulation is the lack of a code that can work at both high scale (to explore large-scale gas turbulence) and small scales (to deal with the individual particles), the two regimes being highly different in terms of priorities towards which to optimize computational efficiency. A general study of planetesimal accretion from dust to 100 km and up is thus still missing. As a first step towards building up a computational solution for merging the two regimes, enabling us to follow the whole turbulence-driven accretion, we use the n-body code PKDGRAV [5] to explore the range of parametres of high density, small particles clusters during their collapse by gravitational instability.

2. Time and lenght scales involved

Several typical timescales are involved in the accretion process [3]: the orbital period T, the gravitational free fall time $\tau_{Gf} \propto \rho^{-1/2}$, the scattering time $\tau_{Gs} \propto \bar{v}^3/m_p^2 n$, the collision timescale $\tau_c \propto 1/r_p^2 \bar{v} n$, the gas drag stopping time $\tau_g = k r_p^\alpha (\mathbf{v}_g - \mathbf{v}_p)$ [m_p, r_p and $\mathbf{v}_p$ being particle mass, radius and velocity, and ρ, n and $\bar{v}$ being the overall mass and particles densities and typical velocity dispersion within the cluster]. They can be used to quantify the action of the different factors acting on the particle dynamics and growth. The ratios of these timescales in a given case will determine which forces will dominate the evolution.

The dynamical and collisional timescales reflect the variety of typical length scales involved in the system, mainly the distance from the Sun a, the cluster dimensions, the typical unstable wavelegth $\lambda_u \propto \Sigma T^2$ [7], the mean free particle path $l_f \propto 1/r_p^2 n$ and the particle size r_p [Σ being the surface mass density of the disk].

3. Super Particle approximation

To correctly represent a typical accretion scenario for even a modest, km-size planetesimal starting from cm-size pebble, a prohibitive number of numerical particles is needed (several 10^{15} in the supposed case, as not all mass will accrete), vastly surpassing the computational capacities. Thus, an expedient is necessary than can relieve the burden without compromising the relevant physical properties of the ensemble. To reduce the number of particles involved, super-particles will be used, each one representing the mass of a large number of smaller ones so to maintain the desired overall masses and gravitational field with $\approx 10^5$ particles.

To correctly proceed, an analysis of the timescales is due. One typical problem being that of having to suppress the effects of gravitational scattering: as the gravity scales with the mass, the super- particles have a much higher effect at the typical interparticle distances of the cluster, which will tend to randomize the velocities too rapidly possibly spoiling the faithfulness of the simulation. Even gas drag scaling must be considered: the effect of gas is in fact much smaller for large super- particles than what would be for the real ones. A simple drag efficiency amplification is however not a suitable solution, as when the particles settle down and begin forming a planetesimal, the aggregated super-particles will represent really aggregated microparticles, the different scales no longer playing any physical role, in which case the gas must act at the ordinary (non-amplified level).

A fine solution to both problems seems to be to consider initial super-particles of artificially inflated volume and low density, to increase the drag effect and to avoid them passing too close to each other thus reducing gravitational scattering, and to revert to real densities (1-3 g/cm^3) once they accrete on each other (that is, when they collide with sufficiently low relative velocity).

4. Accretion process and conclusions

As a main body starts accreting, it will feel less and less the effects of the gas, eventually entirely uncoupling from it, while a disperse cloud of unaccreted particles is still strongly tied to it. Supposing a gas mean motion around the Sun at less-than-keplerian speed, the protoplanetesimal will tend to exit the turbulent region that caused its birth. The fate of the system is then governed by the ability of this body to drag the other particles with it, or to congregate rapidly with similarly created gravitational aggregates.

The goal of the work is to explore which solid and gas disk scenarios are best suited for planetary formation; the range of parameters variation being very large, some educated guesses are to be made after the first wave of trials.

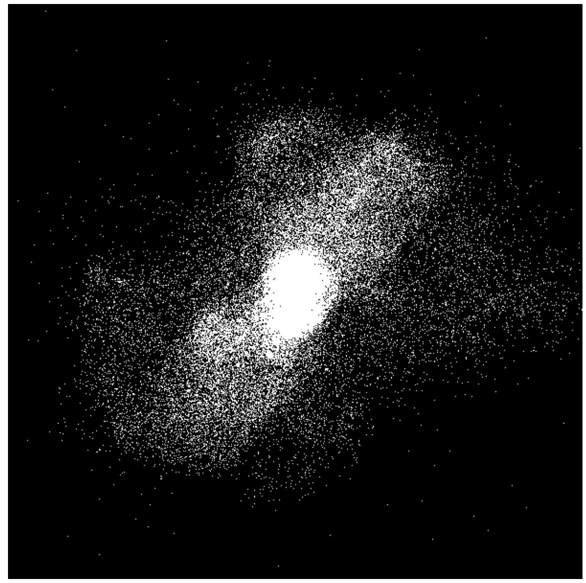

Figure 1: A collapse of an initially $2.5 \cdot 10^{-3} AU$-wide, 2.5 Ceres masses $(2.3 \cdot 10^{21} kg)$ rotating cluster composed of 10^5 (super-)particles orbiting at 5 AU from the Sun; width of the figure is $2 \cdot 10^{-2}$AU.

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