Rapid accretion of large planetesimals by gravitational instabilities

Anders Johansen[1], Andrew N. Youdin[2] and Yoram Lithwick[3], [1]Lund Observatory, Lund University (anders@astro.lu.se), [2]Harvard-Smithsonian Center for Astrophysics, [3]Department of Physics & Astronomy, Northwestern University

The formation of km-sized planetesimals from smaller cm-dm sized particles faces major difficulties in the traditional coagulation scenario. Such particles do not stick well and very quickly drift towards the star to sublimate in the inner nebula. I will present an alternative scenario where overdense regions of particles collapse under their own gravity to form massive 1000-km-scale planetesimals. The overdensities are seeded by hydrodynamical streaming instabilities arising in the coupled motion of gas and particles. New computer simulations that include particle collisions show the perseverance of planetesimal formation by this route. Planetesimal masses are relatively independent of the computational resolution and the simulations reveal a characteristic planetesimal size that increases with distance from the sun. The resulting planetesimal sizes agree well with the observed largest bodies residing in the asteroid and Kuiper belts.

Streaming instability

Planetesimal formation takes place in a complex environment of turbulent gas interacting via drag forces with particles of many sizes. The *streaming instability* thrives in the systematic relative motion of gas and particles and leads to spontaneous clumping of particles [1, 2, 3]. The gravity from the star is partially compensated by the radial pressure gradient of the gas, causing gas to orbit at a slightly slower speed than Keplerian. Clumping is initiated as initially very low amplitude particle overdensities accelerate the gas towards the Keplerian speed, hence reducing the local head-wind on the particles, which in turn slows the radial drift of the particles. Drifting particles pile up where the head-wind is slower, causing exponential growth of the particle density as the particles continue to increase their drag force influence on the gas [1].

While the latest years have seen major progress in numerical modelling of drag force interaction between particles and gas as well as the self-gravity of the particle layer [4], good algorithms for treating simultaneously collisions between the particles are still missing.

Collisions

We have developed a statistical approach to model the full momentum exchange and energy dissipation in collisions between superparticles [5]. The Monte Carlo scheme is inspired by the collision algorithms presented by Lithwick & Chiang [6] and by Zsom & Dullemond [7]. The essence of our algorithm is to determine the collision time-scale between all superparticle pairs within a grid cell. Two superparticless collide as if they were physical particles touching each other, if a random number is smaller than the ratio of the hydrodynamical time-step to the collision time-scale.

Results

Our simulations show that collisions are important to consider when modelling particle concentration by the streaming instability. Taking into account the energy dissipation in inelastic collisions increases the maximum particle density.

Including the self-gravity of the particles, we find formation of gravitationally bound clumps, relatively independently of numerical resolution and treatment of collisions. Results of 128^3 simulations are shown in Figure 1 (see next page). The treatment of collisions has no apparent effect on the planetesimals which form by self-gravity. The masses of the most massive planetesimals are relatively independent of the inclusion or absence of collisions, although we find some evidence that more low-mass clumps condense out in simulations without collisions.

Our local shearing-box simulations are scale-free and this allows the results to be applied to any orbital distance from the star. The simulations show a characteristic planetesimal mass-scale comparable to the dwarf planet Ceres at the location of the asteroid belt [4, 8]. The mass-scale increases approximately linearly with distance from the central star, giving almost double the contracted radius at the distance of the Kuiper belt. This scaling may explain why the largest Kuiper belt objects are bigger than the largest asteroids.

References

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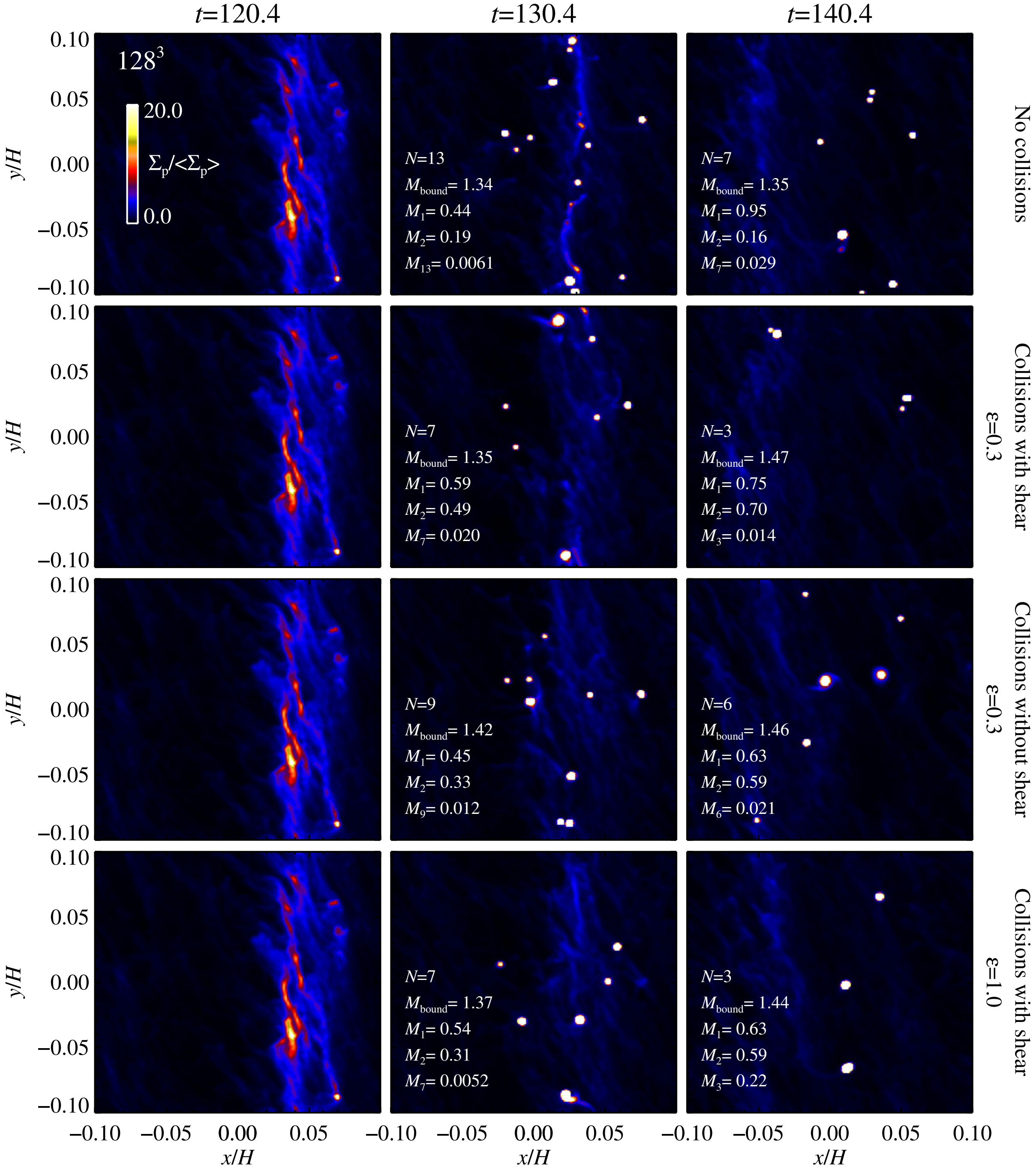

Figure 1: This figure shows the column density of particles after self-gravity is turned on. The three columns show three different times, while the four rows show different treatments of collisions. The simulation box corotates with the Keplerian flow at an arbitrary distance from the central star, with the x-axis pointing radially away from the star and the y-axis pointing along the main Keplerian flow. Gravitationally bound clumps condense out of the overdense filament (second column). The clumps have initial masses between 0.5% and 50% of the dwarf planet Ceres. Mergers subsequently reduce the number of planetesimals (third row). This is likely a numerical artifact, since planetesimals are not allowed to contract below the grid scale.