Formation of planetesimals in collapsing particle clouds

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Dust coagulation and planetesimal formation

The first step of planet formation in a protoplanetary disk is coagulation of µm-sized dust particles. This works up to ~mm-cm sized particles when contact forces are too small to hold the particles together. Also, at high relative speeds (≳1 m/s, Güttler et al. 2010) collisions tend to result in fragmentation instead of coagulation. One way to solve this is to have a self-gravitating cloud of pebbles that is in virial equilibrium. The total energy of the cloud is:

$$E \sim -\frac{3GM^2}{10R}$$

In the cloud, particles would move around and collide with each other. Collisions dissipate away energy from the cloud (unless they are completely elastic) and increase the binding energy. As the cloud loses energy it contracts and the particles start to move faster and faster due to the negative heat capacity nature of self-gravitating systems. This means that the collision rate increases, the cloud loses energy even faster and you get a runaway collapse.

Such a cloud can be formed through the so called streaming instability (Youdin & Goodman 2005). One difference between the gas and the particles in a protoplanetary disk is that the gas feels an outwards force from the pressure gradient in the disk. This means that the gas can orbit with a speed lower than Keplerian and still balance the gravity from the star. The particles feel a headwind, lose energy and drift towards the star. If the particles clump together they will drift slower, catch single particles coming from outside and the clump will grow larger and larger.

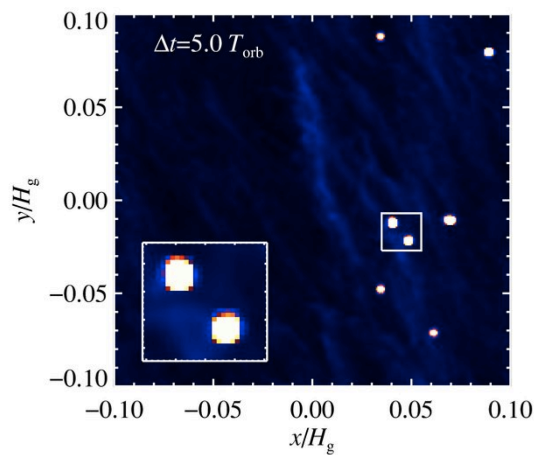

Figure: Formation of gravitationally bound clouds of cm-sized pebbles by the streaming instability (Johansen, Youdin & Mac Low 2009). Unresolved pebble clouds with masses similar to Ceres or Pluto forms in only a few orbital periods.

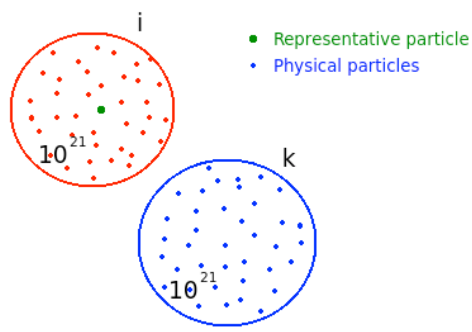

Figure: Collision between two swarms of particles *i* and *k*. The rate with which the representative particle (green dot) collides with any physical particle (blue dots) is used for this particular collision pair. If the collision occurs, the outcome is 'applied' to all particles in the red swarm. Note that a representative particle can collide with its own swarm of particles, i.e. $i = k$.

Representative particle approach

One Pluto mass split into cm-sized pebbles results in $N \sim 10^{24}$ pebbles. This means that there are too many pebbles to keep track of every individual particle but instead you can use a statistical approach to the problem. To investigate the evolution of self-gravitating pebble clouds I use the representative particle approach of Zsom & Dullemond (2008).

The underlying idea is that you follow the evolution of a smaller number, $N' \ll N$, of representative particles instead of all physical particles. The number of these representative particles still has to be large enough such that they mirror the true distribution of particles. One can think of the representative particles as swarms of identical particles.

The evolution of a particle clump is dependent of particle collisions. The figure to the left shows the idea behind a collision between representative particle *i* and a physical particle from swarm *k*. The collision rate can be written as

$$r_i(k) = n_k \sigma_{ik} \Delta v_{ik}$$

where n_k is the number density of particles *k*, σ_{ik} is the cross-section and Δv_{ik} is the relative velocity. From the total collision rate (sum over all possible collision pairs) you get the time until next collision and from the individual rates you can get the two swarms involved in the collision. Next you calculate the outcome of the collision: Do the particles stick, fragment or bounce? How much energy is dissipated? What are the new particle properties (size, velocity, ...)?

Evolution of a particle clump in virial equilibrium

By assuming dissipative bouncing as the only collisional outcome the problem becomes analytically solvable. The size, *R*, of the cloud as function of time, t, can be written as

$$R = \left(1 - \frac{t}{t_{\mathrm{crit}}}\right)^{2/7} R_0$$

where R_0 is the original size of the cloud and $t_{crit} \sim 0.73$ year is the time it takes for the cloud to collapse to a single point if we start out with cm-sized pebbles and a cloud radius of one Pluto Hill radius.

This is, however, not physically realistic. It takes some time for the cloud to get into virial equilibrium after a collision, of order the free-fall time of the system (~25 years for the Pluto Hill sphere). Another problem is that bouncing is not the only outcome. By including fragmentation, the collision rate skyrocket after a cm-sized pebble fragments into µm-sized dust (a factor 10^{12} increase in number density). This results in an increase in the simulation time which is solved by pooling up many collisions at once.

The figure to the right shows the evolution of the size of a pebble cloud including corrections to the problems with the analytic approximation. The cloud still collapses on a timescale shorter than the free-fall time which can be explained with the fact that the free-fall time decreases as the cloud collapses. The mass fraction in µm-sized dust is also included and one sees that the fraction grows to one which means that the pebbles are first ground down to dust and that bouncing collisions between dust particles are the major contributor to the dissipation of energy. One can also conclude that a Pluto formed by this mechanism does not contain any primordial pebbles. A lower mass object (e.g. a comet) might, however, since the collision speeds is determined by the mass of the cloud.

One thing I want to find from this project is the initial mass function of planetesimals so the outcome of a collapsing pebble clump is very relevant. In the future I plan to go from these 0-D simulations to higher dimensions (e.g. Nesvorný et al. 2010).

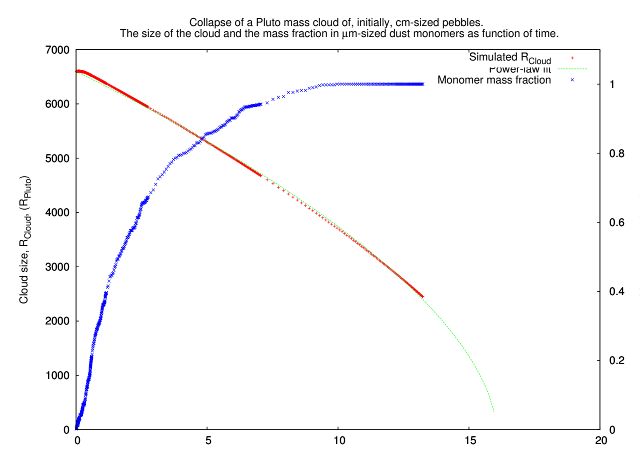

Figure: Results of a simulation of the evolution of a particle cloud that is contracting due to dissipation of energy in particle collisions. All possible outcomes, time for virialization and pooling of collisions are included in the simulation. The red crosses show the size of the cloud and the green line is a fit to the data. The blue crosses display the fraction of mass that is in µm-sized dust monomers. The results show that the relative speed between particles is high enough to fragment the pebbles and form a cloud made, purely, out of dust after only ~10 years. This cloud will quickly collapse into a solid body.

The initial size of the pebbles is one cm and the initial size of the cloud is one Pluto Hill sphere.

References

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