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DYNAMICAL STUDY OF THE COLLAPSE OF A CLOUD OF GAS AND PARTICLES:
WHAT ARE THE THERMODYNAMICAL PROPERTIES OF THE FORMED PLANETESIMALS?

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Abstract. We present work that aims to confront geochemical information on the formation of planetesimals with dynamical studies of the nebula in which they grow from pebbles of around cm in size. A possible scenario consists of the concentration of these pebbles through interaction with the gas in the disc to form clumps, leading to a gravitational collapse and the formation of planetesimals. On the other hand, the geochemical approach of planet formation constrains these conditions as it shows that high temperatures should be reached to form the material of meteorites or to allow the incorporation of gas into planetesimals. In particular, the origin of noble gases in the terrestrial mantle is still debated and might ultimately provide a unique clue on this stage of planet formation. We study numerically the gravitational collapse of a cloud of particles and gas coupled by fluid friction. Our goal is to determine how the gravitational energy relaxed during the collapse will be divided into the different components of the system, and how this constrains the physical and thermodynamical conditions at the surface of the planetesimal.

We present here the numerical tools used for this study and the first results.

Keywords: gravitational collapse, pebbles, gas, fluid friction

1 Introduction

The ubiquity of planets shows that planet formation is a standard process. Protoplanetary disks with sizes of hundreds of AU are factories able to convert dust 20 orders of magnitude smaller into planets. This necessarily involves many different physical and chemical processes. In the incremental growth scenario, the micrometric dust grains agglomerate to form pebbles of around cm sizes (e.g. Armitage (2020)). The following step, the formation of kilometer size objects, planetesimals, is one of the major open questions in this domain. A possible scenario consists of the concentration of these pebbles through interaction with the gas in the disc to form clumps (Drazkowska et al. 2023) which would collapse to form planetesimals. Whereas the step of pebble concentration in the disc is often studied, for example with the process of streaming instability (e.g. Carrera & Simon (2022)) or of dust trapping in vortical structures (e.g. Gerosa et al. (2023), Chavanis (2000)), the step of the gravitational collapse has rarely been studied, mainly to know how one can form binary planetesimals (). On the other hand, the geochemical approach of planet formation shows that high temperature should be reached to form the material of meteorite, or to incorporate gas into planetesimals. Indeed, the origin of noble gas in the terrestrial mantle is still debated and should be consistent with the dynamical processes involved in planet formation. However, the coupling between the dynamics of solids and the gas temperature during the gravitational collapse of a pebble clump in a gaseous environment has rarely been taken into account. This work aims to study numerically the gravitational collapse of a cloud of particles and gas coupled through fluid friction. The aim is to estimate how the gravitational energy relaxed during collapse will be divided into the different components of the system and therefore the temperature the system can reach.

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2 Numerical Methods

2.1 Model

This numerical study of the collapse requires to model the coupled evolution of gas and particles. The gas is modelled as an Eulerian fluid for which the Euler equations are solved:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \tag{2.1}$$

$$\frac{\partial}{\partial t}(\rho u) + \nabla \cdot (\rho u \otimes u) = -\rho \nabla \phi_g - f_{\mathrm{drag}} \tag{2.2}$$

$$\frac{\partial}{\partial t}(\rho e) + \nabla \cdot \left(\rho u (e + \frac{p}{\rho})\right) = \rho u \cdot \nabla \phi_g + E_{\mathrm{drag}} \tag{2.3}$$

The pebbles are modelled as Lagrangian particles for which we solved Newton's law of motion :

$$\frac{\mathrm{d}^2 x}{\mathrm{d}t^2} = -\nabla \phi_g + f_{\mathrm{drag}} \tag{2.4}$$

The self-gravity of the system is taken into account by solving the Poisson equation :

$$\Delta \phi_g = 4\pi G \rho_t \tag{2.5}$$

where ρ_t is the total mass density of gas and pebbles. In these equations, f_{drag} corresponds to the drag force exerted by the gas on pebbles and its feedback onto the gas. We choose to use Epstein drag law (Epstein 1924) such that, for a lagrangian particle with speed v_p :

$$f_{\mathrm{drag}} = -\frac{v_p - u}{\tau} \tag{2.6}$$

where τ is the dust stopping time, depending on the density and the sound speed of the gas.

These equations are solved by using the Idefix code (Lesur et al. 2023). This new numerical code allows us to solve hydrodynamical equations on a grid with a finite-volume Godunov method. A self-gravity module solving the Poisson equation through algebraic methods and a Lagrangian particles module (including gas friction) are currently developed and allow us to take into account the different physics needed for the simulations.

2.2 Initial and Boundary Conditions

All the simulations presented are 1D in spherical geometry. Thus, only the radial movement of the collapsing pebble clump is followed. In the initial state, the Lagrangian particles modelling the dust have no initial speed, and with a density profile chosen as follows:

$$\rho_p(r) = \begin{cases} \rho_c \text{ if } r \leq r_c \\ \rho_c \exp\left(\frac{(r - r_c)^2}{\sigma^2}\right) \text{ else} \end{cases} . \tag{2.7}$$

The initial radius of the pebble clump is defined as $R_0 = r_c + \sigma$ and $\sigma = \frac{r_c}{5}$. The total mass of pebbles is $M_{tot} = \int_0^{+\infty} 4\pi r^2 \rho_p(r) \mathrm{d}r$. The gas is also initially static, with a uniform density ρ_g and temperature T_g across the grid. It is supposed to be perfect. The characteristic time of the drag law was chosen equal to 9×10^4 s which corresponds (with the chosen gas density and sound speed) to pebbles with a size of about 10 cm.

We choose to explore the variations of the final temperature with the total mass of pebbles and the initial density of the gas. M_{tot} goes from 1 to 15×10^{16} kg and ρ_g goes from 3 to 21×10^{-6} $\mathrm{kg \cdot m^{-3}}$.

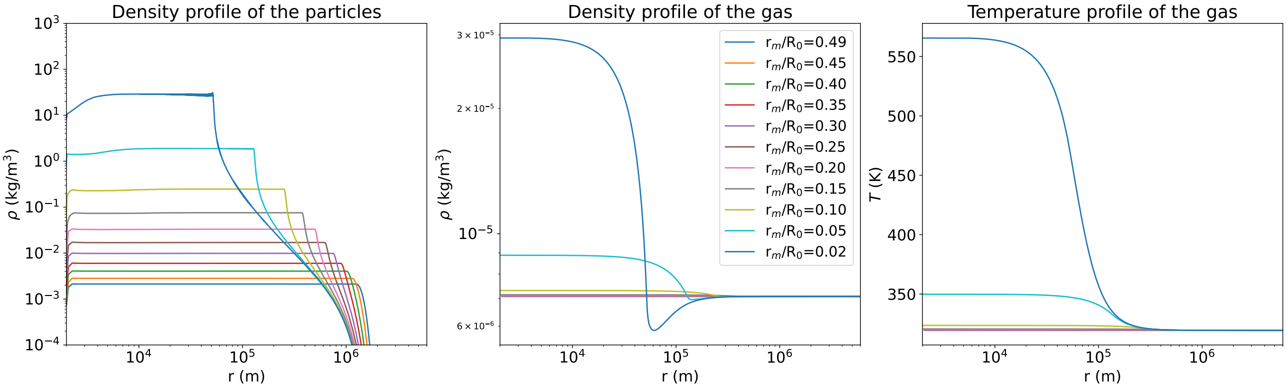

Fig. 1: Radial profile of the particle cloud's density (left), of the gas density (centre) and temperature (right) during the collapse, for $M = 3 \times 10^{16}$ kg, $R_0 = 1,5 \times 10^6$ m, $\rho_g = 7 \times 10^{-6}$ kg/m^3.

3 Results

3.1 Time evolution

We study the evolution of the cloud properties during the collapse. This evolution is shown on the figure 1, in our fiducial case with $R_0 = 1.5 \times 10^6$ m, $M_{tot} = 3 \times 10^{16}$ kg, $\rho_g = 7 \times 10^{-6}$ kg $\cdot$ m^{-3} and $T_g = 320$ K. From left to right, this figure shows the density of the particle cloud, the density of the gas and its temperature. Each curve corresponds to a different time, characterised by the mean radius r_m of the pebble clump at that time, defined as

$$r_m = \frac{\int_0^{+\infty} r\rho_p(r)\mathrm{d}r}{\int_0^{+\infty} \rho(r)\mathrm{d}r}. \tag{3.1}$$

The density of pebble clump, shown on the left of figure 1, increases regularly with time during the collapse, to reach 3×10^1 kg $\cdot$ m^{-3}. The core of the cloud has a uniform density during nearly all the collapse but the concavity of the tail changes and the edge of the cloud becomes steeper. On the contrary, the density of the gas (at the centre of the figure) and its temperature (on the right) are nearly constant during the collapse and change only at the end of the collapse, with finally a multiplication by 4 of the central density, and an increase of about 240 K of the central temperature of the gas.

3.2 Parameter Space Exploration

We studied the evolution of the final central temperature of the gas with two main parameters: the total mass of the cloud M_{tot} and the initial density of gas ρ_g. As shown in the left panel of Fig. 2, the final temperature is approximately inversely proportional to the initial density of gas. However, we see that the slope of the curves varies slightly with the initial mass of the cloud. To better understand this behaviour, we also plotted the final temperature as a function of the initial mass, as shown on the right panel of 2. We see that the final temperature is approximately proportional to the initial mass, but again, the slope depends slightly on the density of the gas. These slight variations are not for now fully understood and we project to explore in more detail the parameter space to explain that.

These behaviours are consistent with those we can expect theoretically: the more massive the pebble clump is, the more energy the system will release and so the hotter the gas will be in the vicinity of the forming planetesimal. Likewise, if less gas is surrounding the clump, then, for the same energy released, the gas will be hotter. These results show that, to dissolve gas from the disc into the forming planetesimal (i.e. reach a temperature of about 1200 K), we need to have a quite massive clump (mass of around 10^{17} kg that is a planetesimal of around 10 km in size) with low surrounding gas density (initial dust-to-gas ratio of around 1000 and above).

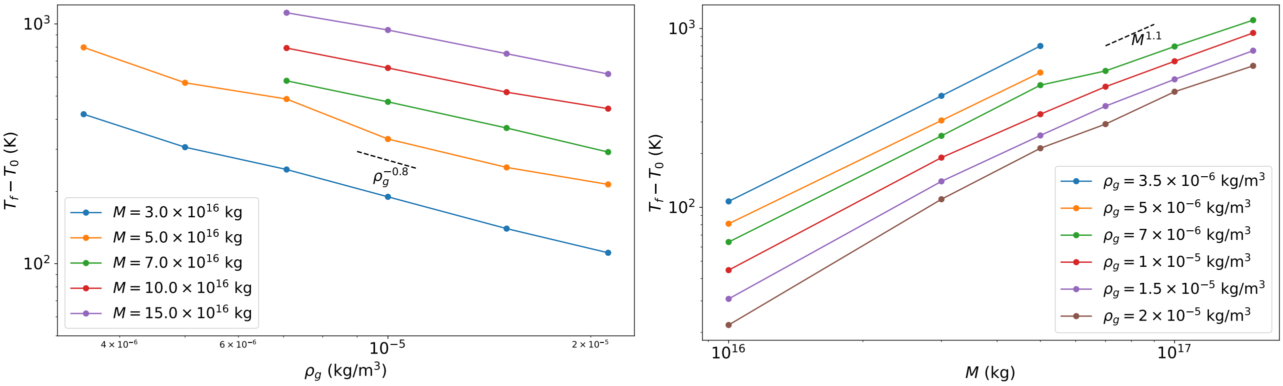

Fig. 2: **Left:** Gas central temperature as a function of the initial gas density for different values of the initial mass of the particles cloud ($R_0 = 1,5 \times 10^6$ m). **Right:** Gas central temperature as a function of the initial mass of particles for different values of initial gas density

4 Conclusion

Through these simulations of gravitationally collapsing pebble clumps, we were able to demonstrate the importance of the heating of the gas surrounding the clump. We expose the main dependencies of this heating with the clump mass and the gas density. We show that the clump should be sufficiently massive in order that the temperature of the gas is enough to dissolve itself in the forming planetesimal. This is consistent with small bodies of the solar system for which the smallest bodies do not have traces of heating processes during their history.

However, the simulations present several limits which could nuance our results. First, as we were doing 1D simulations, we completely neglected collisions and thus neglected the process of redistribution of kinetic energy and momentum between pebbles, which could then impact the temperature profile of the gas. Second, we made the hypothesis that only the gas is heated and not the pebbles, but if the gas is at around 1000 K but the pebbles are at the initial temperature of 300 K, thermal exchanges between them will cool the gas.

This work opens new paths for the exploration of the gravitational collapse of a pebble clump in a gaseous environment: first by extending the simulations to 2D or 3D, allowing to take into account initial velocity dispersion and collisions, and second by modelling better the thermal exchanges between pebbles and gas.

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