SF2A 2021
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DUST GRAINS SHATTERING IN PROTOPLANETARY DISCS: COLLISIONAL FRAGMENTATION OR ROTATIONAL DISRUPTION?

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Abstract.
Coagulation of dust grains into large aggregates still remains poorly understood. Grain porosity appears to be a promising solution to allow the grains to survive and form planets. Furthermore, dust shattering was considered to come only from collisional fragmentation, but a new process was introduced, rotational disruption. We wrote a C++ code to model grain growth and porosity evolution to study the final outcome of grains under the two shattering processes. When considering a disc model that reproduces observations, we point out that rotational disruption is negligible compared to the fragmentation and radial drift in almost all cases, and can therefore be neglected for commonly used values of fragmentation threshold and viscosity in 3D hydrodynamic simulations.

Keywords: protoplanetary discs, planet formation, dust, coagulation,

1 Introduction

In the theory of planetary formation, growth of sub-μm to mm dust aggregates in protoplanetary discs into planetesimals is hampered by theoretical problems commonly known as the radial drift barrier and the fragmentation barrier, preventing dust grains to survive and lately create planets. A promissing solution to overcome these barriers is to consider intrinsic dust properties, namely grain porosity. For a given mass, fluffy grains have a larger collisional cross-section allowing them to grow faster, while staying coupled to gas at larger sizes, assuring their survival in the disc.

Recently, rotational disruption of porous dust grains was proposed as another possible barrier and has been investigated by Tatsuuma & Kataoka (2021) in the framework of protoplanetary discs. They found that grains can be disrupted by the gas-flow torque when aggregates tend to be highly porous, before they can decouple from the gas, when very compact grains subject to stronger radial drift are not.

We have developed a simple 1D C++ code to understand the behaviour of porous grains under the influence of different physical processes such as gas drag and grain growth. We incorporate the physics of a simplified rotational disruption model based on Tatsuuma & Kataoka (2021) in our code. We studied the behaviour of dust grains to understand in which case each shattering process, fragmentation due to collision between grains or rotational disruption dominates.

2 Theoretical background

To model protoplanetary discs, we adopt the commonly-used formulation in power-law of gas disc. For a stationary disc, two indices p and q can be defined to express the surface density profile $\Sigma_{\rm g} \propto R^{-p}$ and temperature profile $T_{\rm g} \propto R^{-q}$ as a function of the distance to the star R, assuming a vertically isothermal profile for the gas. We choose here to use a model of disc that reproduces observations. The star mass is set to $M_{\rm star} = 1$ M$_\odot$, the disc mass to $M_{\rm disc} = 0.01$ M$_\odot$. Inner, outer and reference radii of the disc are $R_{\rm in} = 10$ AU, $R_{\rm out} = 300$ AU and $R_0 = 1$ AU. Finally $p = 1$, $q = 1/2$ and the disc aspect ratio at R_0 is $\frac{H_{\rm g,0}(R)}{R_0} = 0.0283$.

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2.1 Growth and fragmentation model of dust grains

In this study, we focus on the evolution of porous aggregates. To model grain growth, we consider a locally mono-disperse mass distribution where collisions between identical grains occur. Grains collide with a relative velocity $v_{\rm rel}$ due to the gas turbulence transmitted to the dust by drag. $v_{\rm rel}$ can be expressed as:

$$v_{\rm rel} \propto \sqrt{\alpha}\frac{\sqrt{\rm St}}{1+{\rm St}}c_{\rm g}. \tag{2.1}$$

Here, $c_{\rm g}$ is the gas sound speed and α is the turbulent viscosity parameter defined by Shakura & Sunyaev (1973). To express the coupling between gas and dust, we define the Stokes number ${\rm St} = \tau_{\rm s}/t_{\rm K}$ as the ratio between the stopping time $\tau_{\rm s}$, i.e. the time needed for a grain to reach the gas velocity, and the keplerian orbital time $t_{\rm K}$. Depending on the value of St, grains behave differently, and three situation can be distinguished. If ${\rm St} \ll 1$, dust grains are typically small and well coupled to the gas. Thus, grains orbit at the sub-keplerian velocity of the gas. If ${\rm St} \gg 1$, dust grains are large enough to be almost completely decoupled from the gas, orbiting at a keplerian velocity. However, when ${\rm St} \approx 1$, dust grains have an intermediate size and gas drag is important. Therefore, the gas friction applied on the grains force them to slow down and they radially drifts toward the star due to the loss of angular momentum to be accreted onto the star. This is the radial drift barrier. Lastly, to model fragmentation of dust aggregates, we use the model developed by Kobayashi & Tanaka (2010) and Garcia (2018) where the loss of mass is also a function of the fragmentation threshold $v_{\rm frag}$.

2.2 Porosity evolution model

To take into account grain porosity, we use a reformulated and simpler version of the algorithm derived by Garcia (2018) and Garcia & Gonzalez (2020) based on the model of Suyama et al. (2008), Okuzumi et al. (2009), Okuzumi et al. (2012) and Kataoka et al. (2013). Details are presented in Garcia & Gonzalez (2020).

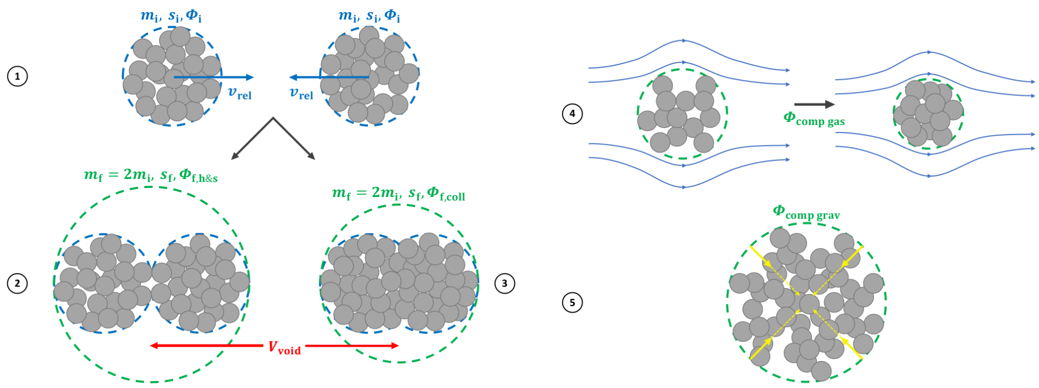

Fig. 1. Left: 1) Two identical grains collide with each other with a relative velocity $v_{\rm rel}$. 2) In the "hit & stick regime", grains simply stick together, a new volume of void is formed. 3) In the collisional compression regime, the new grains suffer internal restructuring. **Right:** 4) Grains can be compressed by the surrounding gas flow. 5) Massive grains can also be compressed by their own self-gravity.

A dust aggregate is a collection of n monomers considered to be compact spheres of mass m_0, size a_0 and intrinsic density $\rho_{\rm s}$. We define the filling factor $\phi = \rho/\rho_{\rm s}$ as the ratio between the mean internal density and the intrinsic density of the monomers which compose the aggregate. The mass m of the aggregate of size s and mean internal density ρ can be computed as followed:

$$m = \rho V = \rho_{\rm s}\phi\frac{4\pi}{3}s^3. \tag{2.2}$$

Depending on the mass of the grain, two regimes of expansion or compression drive the evolution of the aggregate. In the "hit & stick" regime (see figure 1 left), grains are small and coupled to the gas. For each collision, the mass doubles and a new volume of void is captured. When grains grow, the kinetic energy at impact increases and collisional compression appears. As $v_{\rm rel}$ depends on the Stokes number, the final filling factor takes a different expression in each drag regime (see Garcia & Gonzalez 2020). Independently of collisions, grains can also suffer static compaction (see figure 1) due to either gas flow or self-gravity (Kataoka et al. 2013).

2.3 *Rotational disruption*

This year, Tatsuuma & Kataoka (2021) presented a new barrier to dust growth: the rotational disruption barrier. Rotational disruption has already been investigated for interstellar medium dust or cometary dust, but not in the case of protoplanetary discs. We suppose that our grains are always in a steady-state angular velocity regime to be able to compute the angular velocity ω_c, considered to be driven only by the gas-flow torque. We also consider a relatively weak turbulent gas, as strong turbulence has unknown effects on disruption due to non trivial gas flow. To compute when a grain is rotationally disrupted in our simulations, we derive first the tensile stress S of a grain and we compare it to the tensile strength Smax derived by Tatsuuma et al. (2019). For more details, the full calculation is presented in Tatsuuma & Kataoka (2021).

3 Results

To study the effect of disruption, we choose to investigate the effect of the monomer size a_0 with various turbulent viscosity parameters α to compute when icy grains are disrupted. We choose two different monomer sizes: $a_0 = 0.1$ and 1 μm (Güttler et al. 2019). We restrict our study to icy grains with an intrinsic density of $\rho_s = 1000$ kg.m^{-3} and a surface energy of $\gamma_s = 0.1$ J.m^{-2}, because it is a very common species in discs. As the critical rolling displacement is uncertain, we choose, like Tatsuuma & Kataoka (2021), $\xi_{\rm crit} = 8$ Å. For the fragmentation threshold, we choose the typical value of $v_{\rm frag} = 15$ m.s^{-1}. Since turbulence is a key parameter for $v_{\rm rel}$, we choose a wide range of turbulence parameters $\alpha = 10^{-2}, 10^{-3}, 10^{-4}$ and 10^{-5}. As a first step, we run simulations where the grains are in fixed positions to derive when they are disrupted.

A higher turbulence leads to rotational disruption at smaller sizes compared to lower turbulence, where sizes of tens of meter can be reached in a much wider region for aggregates with monomers of 0.1 μm (figure 2). In fact, stronger turbulence leads to higher collisional velocities between grains, making collisional compaction start earlier during their growth. For $a_0 = 0.1$ μm, we can see a slope change close to the star on both panels of figure 2, extending to larger radii when α is smaller, which is due to the gas flow static compression driving the grain evolution when the collisional compression is less efficient at low turbulence. With the left panel of figure 2, we can clearly see that aggregates made of bigger monomers are more susceptible to be disrupted at smaller sizes, as shown by (Tatsuuma & Kataoka 2021). Interestingly, the computed relative velocity $v_{\rm rel}$ between grains just before the disruption remains rather unaffected by the monomer size. For a given α, the difference is only of a few m.s^{-1} as shown in the right panel of figure 2. At an intermediate turbulence of $\alpha = 10^{-3}$, both barriers appear to be in a tight competition.

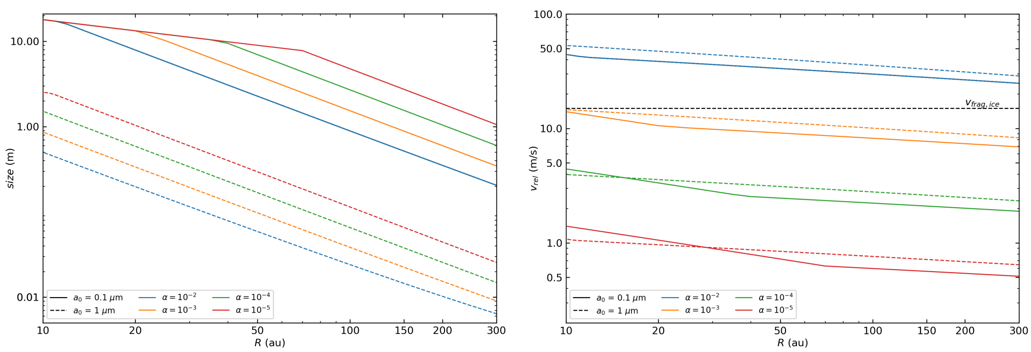

Fig. 2. Left: Maximum grain size before disruption for different α viscosity parameters and monomer sizes a_0 with icy grains. **Right:** Maximum relative velocity between gas and dust before disruption for different α viscosity parameters and monomer sizes a_0 with icy grains. The black dashed line correspond to the typical fragmentation threshold of ice.

Until now, we did not take into account the grains spatial evolution on the disc as orbital position was kept fixed. As we mentioned above for high turbulence ($\alpha = 10^{-2}$), fragmentation is the dominant process (figure

3). The grains start to grow from the monomer size, then slowly drift as St increases, then $v_{\rm rel}$ increases and rapidly exceeds the fragmentation threshold. An equilibrium between growth and fragmentation is reached, maintaining grains in a range of size big enough to allow efficient radial drift and finally get accreted onto the star. For $\alpha = 10^{-4}$ (not shown), neither rotational disruption nor fragmentation destroy aggregates. Very weak turbulence reduces the growth efficiency of fluffy grains too heavily. As the growth rate is smaller, grains are not able to reach in time either the fragmentation barrier or the disruption barrier. The growth rate of meter-sized aggregates is high enough to reach the disruption barrier before grains get accreted for an intermediate turbulence of $\alpha = 10^{-3}$. On figure 3, we plot with dashed lines the trajectory of grains if disruption was not taken into account. For $\alpha = 10^{-3}$, rotational disruption dominates, as grains crossed the disruption limit before exceeding the fragmentation threshold. Nevertheless, the maximum size reached by grains with or without disruption is the same, between 10 and 20 meters.

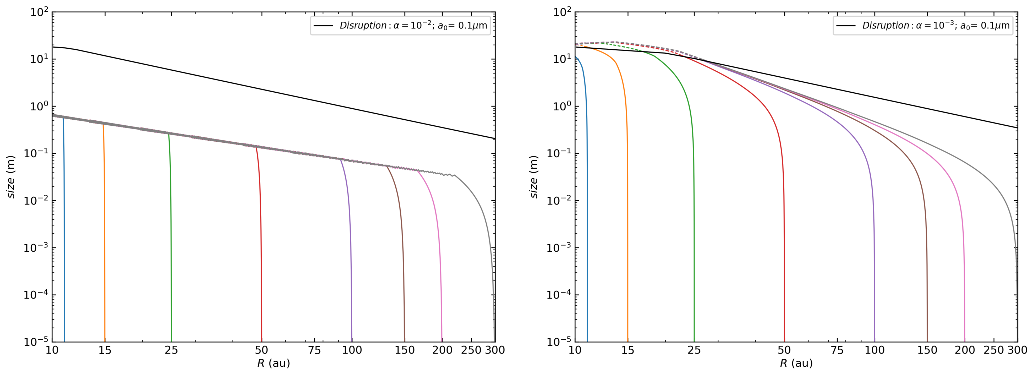

Fig. 3. Evolution of icy grains for three viscosity parameters $\alpha = 10^{-2}, 10^{-3}, 10^{-4}$ and $a_0 = 0.1$ μm

4 Conclusions

We investigate dust grain shattering in protoplanetary discs to understand if rotational disruption is an important process in aggregate evolution. Using our growth and porosity evolution model, we showed that disruption is a marginal barrier and plays a role in a restricted range of parameters $\alpha \approx 10^{-3}$ and $v_{\rm frag} > 10$ m.s^{-1}. For higher turbulence or lower fragmentation threshold, collisional fragmentation rules, while for low turbulence, radial drift prevails. Thus, we can neglect in most cases rotational disruption as it is not the main process of dust grain shattering. Nevertheless, further investigation has to be done. It would be interesting to understand the effect of using different materials such as silicates, another abundant species in protoplanetary discs. The different material properties could change grain evolution significantly.

We would like to thank the SF2A and the PNP workshop for letting us presenting our work to the "journées de la SF2A 2021". Figures in the results section were made using the *matplotlib* library (Hunter 2007).

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