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GROWING POROUS GRAINS: A SOLUTION TO THE RADIAL-DRIFT BARRIER

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Abstract.
Protoplanetary discs are made of gas and dust orbiting around young stars. Initially submicronic, dust grains can grow by coagulation during collisions until they reach millimetre, then kilometer (planetesimal) and planetary sizes. However, theory indicates that once grains reach a size (between millimetre and meter) for which the planet growth timescale is shorter than the accretion timescale, they drift inwards due to the aerodynamical drag force and are accreted onto the star. This effect goes under the name of radial-drift barrier. Several solutions to this problem have been proposed. In this work, we focus on an intrinsic property of grains: porosity. We investigate the effects porosity can have on grain growth and dynamics using an analytical model. Taking only drift into account (no growth), we find that porous grains are slowed down but also tend to be compressed by the gas in the inner parts of the disc. Analysing growth at fixed distance from the star (no drift), we show that porous grains grow faster and more efficiently than compact ones. Combining drift and growth, we demonstrate that porous grains can overcome the radial-drift barrier and keep growing in the inner parts of the disc while compact grains fall into the star.

Keywords: Protoplanetary discs, Planets and satellites: formation, Star: circumstellar matter, Methods: analytical

1 Introduction

The study of planet formation has been revolutionized in the past 20 years as thousands of exoplanets have been discovered (Batalha et al. 2013) with as many different cases as there are planetary systems. We thus need robust tools to understand planet formation. Planets are thought to form in protoplanetary discs, made of gas and dust grains (Lissauer 1993). The growth of very small grains from submicronic monomers to millimeter-sized grains and evolution of large grains from planetesimals to planets are now well known (Blum 2010; Lambrechts & Johansen 2012). However, theoretical and experimental studies demonstrate that when compact grains reach intermediate sizes (from millimetre to meter), they drift quickly, not growing fast enough to decouple from the gas and are accreted into the central star (Weidenschilling 1977). Thus, all the dust reservoir should empty making the growth of planet impossible. Several solutions have been proposed such as particle traps around planet gaps (Paardekooper & Mellema 2004; Fouchet et al. 2010; Gonzalez et al. 2015) or vortices (Barge & Sommeria 1995; Meheut et al. 2012). Porous growth appears to be another solution to the radial-drift barrier (Okuzumi et al. 2012; Kataoka et al. 2013) which could also explain comets' porosity (Lethuillier et al. 2016). In this study, using a model of evolution of porosity during dust growth, we investigate at first the drift of fixed-mass porous and compact grains then growth at fixed distance from the star and finally both drift and growth to study how porosity can influence the grain radial motion, allow grains to reach planetesimal sizes, and overcome the radial-drift barrier.

In section 2, we introduce the different analytical models we have used; in section 3, we present our results and our conclusion in section 4.

2 Method

We study the radial motion and evolution of porous and compact grains using the models described in this section.

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2.1 T-Tauri disc model

We consider a 1D protoplanetary disc of 0.01 $M_\odot$ mass made of 1% of dust and 99 % of gas, extending from 0.1 to 300 AU around a 1 $M_\odot$ T-Tauri star. The disc physical properties are described by power laws of the distance from the star R and is vertically isothermal with $T(R) \propto R^{-3/4}$ and $T(1\ \mathrm{AU}) = 197$ K. The gas surface density Σ is proportionnal to $R^{-3/2}$. In order to represent gas turbulence in the disc, we use the Shakura & Sunyaev (1973) model and set the α-parameter to 10^{-2} (strong turbulence).

2.2 Aerodynamical parameters

Grains evolve in a gaseous environment. As the dust phase is only subject to the gravity of the central star, it rotates with a keplerian velocity. The gas phase is also subject to its own pressure and rotates with a subkeplerian velocity. Therefore, grains undergo a headwind and thus a drag force from the gas. This aerodynamical force can be characterized by the Stokes number St. Two drag regimes can be distinguished according to the radius s of a spherical grain and the mean free path λ of the gas molecules: the Epstein regime ($s \leq 9\lambda/4$) where:

$$\mathrm{St} = \frac{\Omega_\mathrm{k}\, \rho_0\, \phi\, s}{\rho_\mathrm{g}\, c_\mathrm{g}} \tag{2.1}$$

where ρ_0 is the material density, ρ_g and c_g respectively denote the gas density and sound speed, Ω_k, the Keplerian angular velocity and ϕ is the grain filling factor defined as:

$$\phi = \frac{\rho}{\rho_0} \tag{2.2}$$

where ρ is the intrinsic density of the grain. Very porous grains have ϕ close to 0 when compact grains have ϕ equal to 1. If $s \geq 9\lambda/4$, the grain is in the Stokes regime and has:

$$\mathrm{St} = \frac{4\,\Omega_\mathrm{k}\, \rho_0\, \phi\, s^2}{9\,\lambda\, \rho_\mathrm{g}\, c_\mathrm{g}} \tag{2.3}$$

A grain with St ~ 1 physically means that the grain takes a Keplerian orbital period to reach the gas velocity.

2.3 Growth and drift

We use the drift model from Weidenschilling (1977) where the grain radial velocity is always directed inwards towards the center of the star:

$$\frac{dR}{dt} = \mathrm{St}\, \frac{1}{\Omega_\mathrm{k}\, \rho_\mathrm{g}}\, \frac{dP_\mathrm{g}}{dR} \qquad \mathrm{St} < 1 \tag{2.4}$$

$$\frac{dR}{dt} = \frac{1}{\mathrm{St}}\, \frac{1}{\Omega_\mathrm{k}\, \rho_\mathrm{g}}\, \frac{dP_\mathrm{g}}{dR} \qquad \mathrm{St} > 1 \tag{2.5}$$

where P_g is the gas pressure. The radial velocity thus increases with the grain mass for St < 1 and decreases for St > 1 therefore there is a maximum for St ~ 1 corresponding to the radial-drift barrier.

We consider that growth occurs by coagulation during collisions of two identical grains and we use the model from Stepinski & Valageas (1997) where the temporal variation of the grain mass is given by:

$$\frac{dm}{dt} = 4\,\pi\, s^2\, V_\mathrm{rel}\, \rho_\mathrm{d} = m^{2/3} \left(\frac{3\,\sqrt{4\pi}}{\rho_0\, \phi} \right)^{2/3} V_\mathrm{rel}\, \rho_\mathrm{d} \tag{2.6}$$

where ρ_d is the density of matter concentrated into SPH solid particles. As our work is analytical, we fix $\rho_\mathrm{d} = 0.01\, \rho_\mathrm{g}$ according to the dust-to-gas mass ratio defined in section 2.1. V_rel is the relative collision velocity between identical grains defined as:

$$V_\mathrm{rel}^2 = 2^{3/2}\, \mathrm{Ro}\, \alpha\, c_\mathrm{g}^2\, \frac{\mathrm{St}}{(\mathrm{St}+1)^2} \tag{2.7}$$

where Ro is the Rossby number for turbulent motions we take equal to 3.

2.4 Porosity model

Grains grow by coagulation during collisions and this aggregation makes them become more porous (Okuzumi et al. 2012). As the relative velocity between two colliding aggregates increases with their mass, the tiny aggregates (a few monomers) collide with a small relative velocity and stick without internal reorganization, their intrinsic density ρ thus decreases. It is the 'hit-and-stick' regime. For more massive grains, the shock energy is no longer negligible and is dissipated by compressing the aggregates. It is the 'collisionnal compression' regime. However, Kataoka et al. (2013) have found that static compression may also occur. Indeed, grains have a velocity against the gas and experience a ram pressure which can compress them. This is called the 'gas compression' regime. Moreover, grains can become large enough to have their own gravity and be compacted in the 'self-gravitational compression' regime. We derive the equations for the four regimes and find that the intrinsic density is related to the grain mass m as:

$$\rho \propto \begin{cases} m^{-1/2} & \text{hit-and-stick} \\ m^{0} & \text{collisionnal compression} \\ m^{0} & \text{gas compression (Epstein regime)} \\ m^{-1/14} & \text{gas compression (Stokes regime)} \\ m^{2/5} & \text{self-gravitation} \end{cases} \quad (2.8)$$

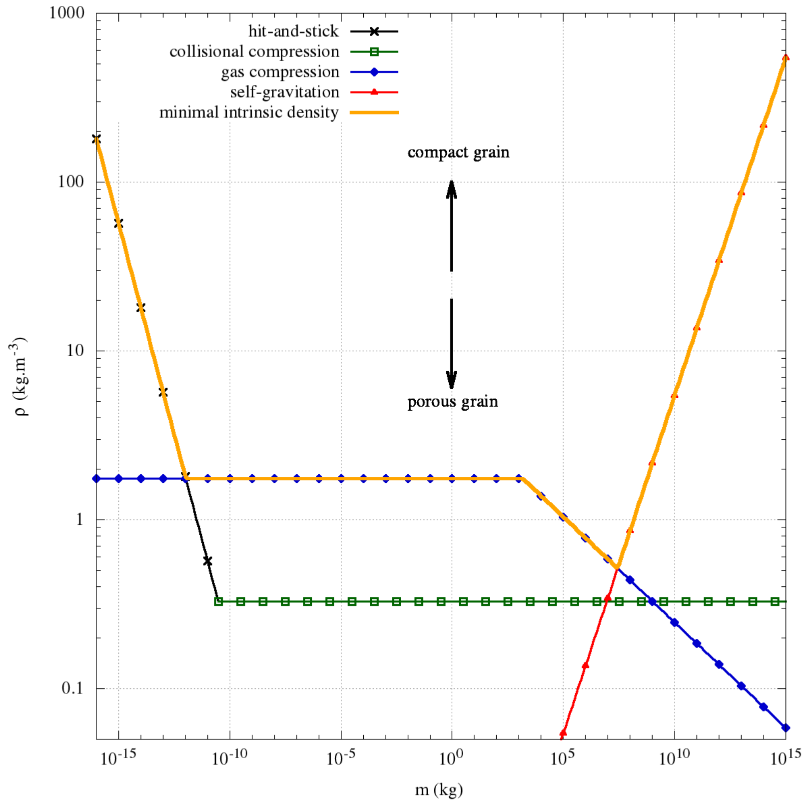

Fig. 1. Intrisic densities calculated for the different regimes as a function of grain mass. We consider icy grains ($\rho_0 = 917$ kg.m^{-3}) at $R = 10$ AU.

Figure 1 shows the variation of the intrinsic density for the different regimes as a function of grain mass. The grain intrinsic density can only decrease in the hit-and-stick or collisional compression regimes and can only increase because of the gas or self-gravitational compression regimes. If a grain has a density above the curves corresponding to gas or self-gravitation compression, it physically means that the grain is compact enough not to be compressed by those two compression mechanisms. On the other hand, if the grain density is below those curves, the grain is too porous and is staticly compressed by its self-gravitation or by the surrounding gas until it becomes compact enough to be in equilibrium with those two mechanisms. Therefore, the upper curves indicate a minimal intrinsic density.

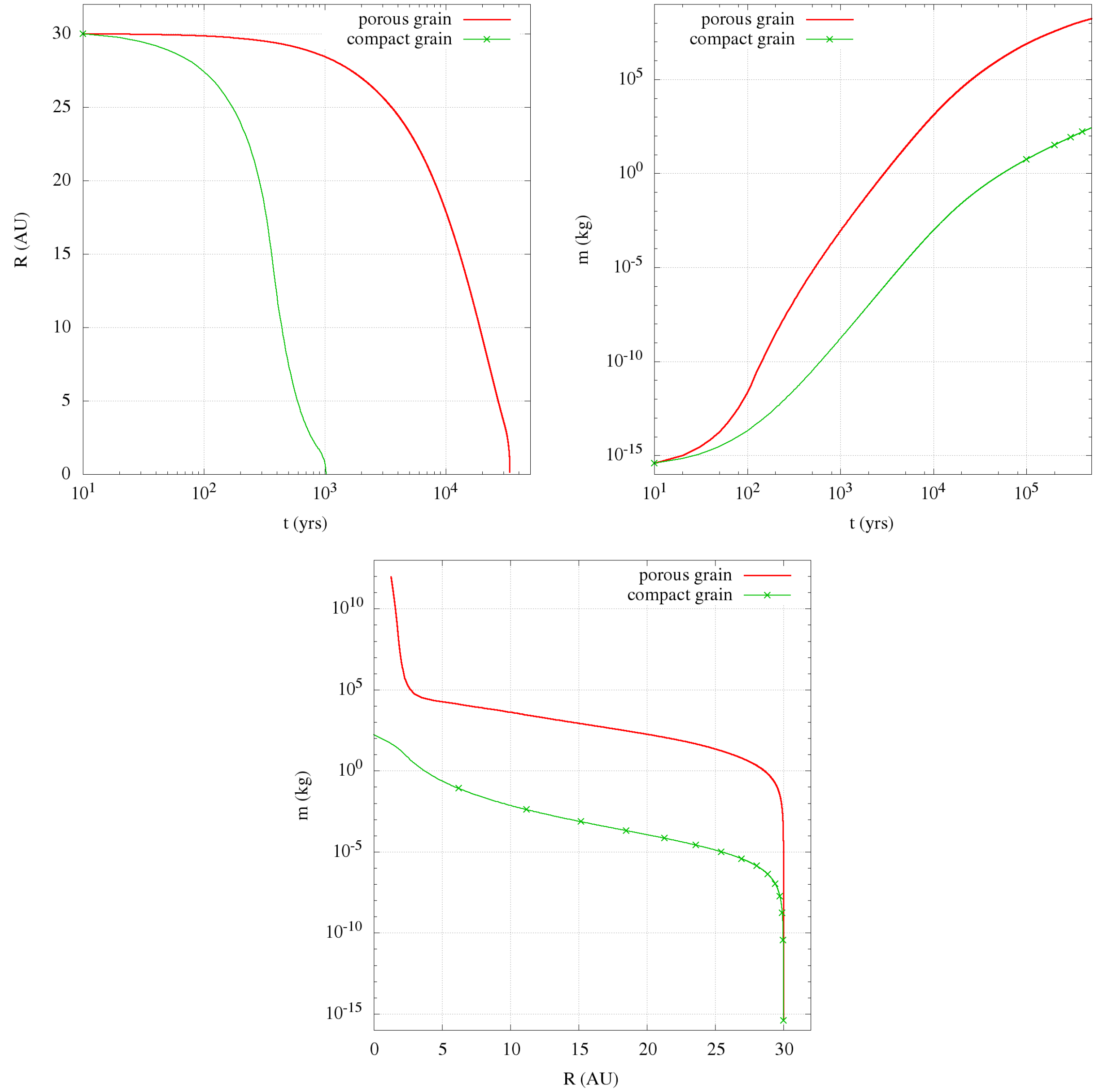

Fig. 2. (a) Top left: Only drift: distance from the star r as a function of time for grains with both a constant mass $m = 1$ kg at initial distance $R_i = 30$ AU. **(b) Top right:** Only growth: grain mass m as a function of time for grains with an initial mass $m_i = 3.84\text{x}10^{-16}$ kg at a constant distance from the star $R_i = 30$ AU. The porous grain has an initial filling factor $\phi_i = 0.1$. **(c) Bottom center:** Drift and growth: Grain mass m as a function of the distance from the star R for grains with an initial mass $m_i = 3.84\text{x}10^{-16}$ kg at an initial distance from the star $R_i = 30$ AU. The porous grain has an initial filling factor $\phi_i = 0.1$. The red curves show the behaviour of an icy grain with the porosity model while the green curves with crosses show that of a compact grain.

3 Results & discussion

Figure 2 (a) shows the temporal evolution of the distance from the star for porous (red curve) and compact (green curve) grains with a constant mass $m = 1$ kg starting from $R = 30$ AU. For porous grains, grain density follows the minimal density defined in section 2.4. We can observe that compact grains are quickly accreted ($\sim 10^3$ years) while porous grains are also accreted but within a longer time ($\sim 3\text{x}10^4$ years). We can conclude that intermediate-sized porous grains are not able overcome the radial-drift barrier with only drift. For intermediate sizes, a porous grain has a larger area-to-mass ratio than a compact grain with the same mass, and as the intensity of the gas drag is proportional to the area-to-mass ratio, the drag is stronger. This slows down the porous grain. However, porous grains are compressed during the drift: going inwards, they pass through the inner parts of the disc where the hot dense gas can statically compress them and thus their resistance to the drift will be less efficient.

Figure 2 (b) shows the evolution of the mass as a function of time, for compact and porous growing grains with the same initial mass $m_{\rm i} = 3.84{\rm x}10^{-16}$ kg[1] at the same fixed distance from the star ($R_{\rm i}$ = 30 AU). We see that porous grains experience a more efficient growth and become $\sim 10^5$ more massive than compact grains after $5{\rm x}10^5$ years. As an interpretation, for a given mass, porous grains have a larger collisionnal cross section than compact grains therefore their probability to collide with other grains and thus grow is higher than for compact grains. Consequently, porosity could accelerate grain growth.

Figure 2 (c) shows the evolution of the mass as a function of the distance from the star for porous and compact grains with an initial mass $m_{\rm i} = 3.84{\rm x}10^{-16}$ kg[1] and an initial distance from the star $R_{\rm i} = 30$ AU. In this final case, both drift and growth are taken into account. We see that during the first stage of growth (up to $\sim 10^3$ years), both porous grains and compact grains grow without a significant drift but porous grains attain larger masses. When they reach St ~ 1, they start to drift but still grow. Even if the growth is more efficient in the inner parts of the disc given the hot and dense gas, compact grains are then accreted into the star. On the other hand, porous grains were already more massive when they start to drift and they reach the inner disc regions with a size which allows them to decouple from the gas, avoiding accretion.

We find that planetesimals[2] can be formed within $\sim 10^4$ years. This can be seen in Figure 2 (c) where the red curve reaches $m = 10^5$ kg, corresponding also to the decoupling of the porous grain close to the star. Even if we continue the growth, our derived timescale and location at which planetesimal size is reached are in a good agreement with Krijt et al. (2016) who have used similar models for porosity and drift. However, planetesimal growth is also driven by accretion of pebbles due to their own gravity (Visser & Ormel 2016) and this type of growth is not taken into account in our model.

4 Conclusion

In this work, we investigate if porosity allows grains to overcome the radial-drift barrier. Our calculations show that the growth of porous grains is faster than that one of compact dust. This can be explained by the fact that, for a given mass, porous grains have a larger cross section. This phenomenon can also explain the slower drift of intermediate-sized porous grains illustrated in section 3. Moreover, grains can be compressed because of the static compression by the dense gas when they reach the inner parts. We show that drift of intermediate-sized porous grains with a constant mass cannot overcome the radial-drift barrier. Drift and growth of porous grain could instead overcome the radial drift barrier. Indeed, porous grains grow more efficiently at their initial radius before they drift while still growing and decouple close to the star where the conditions are favorable to reach planetesimal sizes. Conversely, compact grains do not grow fast enough to decouple and are accreted into the star.

In the next work, we will implement this model in our 3D SPH two-phase code (Barrière-Fouchet et al. 2005). This will allow us to investigate mechanisms which are not taken into account in our analytical study such as turbulence of the gas, collective effects of the dust or backreaction of dust on gas. In order to better understand the evolution of the most massive grains, it would be also interesting to include a model of growth by pebble accretion due to their self-gravity.

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[1] corresponding to the mass of a 1 μm porous grain with a filling factor of 0.1 or that of a 0.46 μm compact grain
[2] objects with St $> 10^3$ according to the definition of Krijt et al. (2016)

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