Growing porous grains: a solution to the radial-drift barrier

A.J.L. GARCIA[1*], J.-F. GONZALEZ[1], F.C. PIGNATALE[1]

1) Centre de Recherche Astrophysique de Lyon - Observatoire de Lyon (France)

* anthony.garcia@univ-lyon1.fr

1 - CONTEXT

In protoplanetary discs, micron-sized grains are known to grow to eventually reach planetesimal sizes. However, dynamical studies show that once they reach a critical size, they rapidly migrate into the accreting star. This is known as the radial-drift barrier (Weidenschilling 1977). In order to overcome this barrier, several methods have been proposed such as particles traps caused by, e.g., vortices, planet gaps, which all involve large-scale dynamics.

In this work, we choose to investigate analytically the intrinsic properties of the grains during their growth, in particular their porosity. Indeed, many objects present in the Solar System including meteorites or comets are porous.

2 - POROSITY

Filling factor ϕ of the grain

$$\phi = \frac{\rho}{\rho_s}$$

ρ: intrinsic density (m/V_{tot})

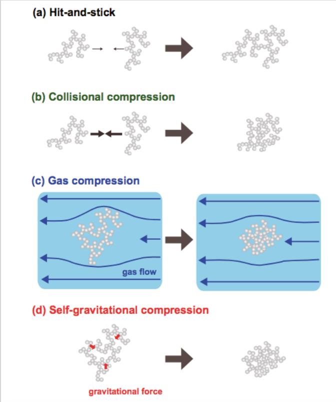
ρ_s: bulk density ($m/V_{compact}$)

0 —— 1 → ϕ

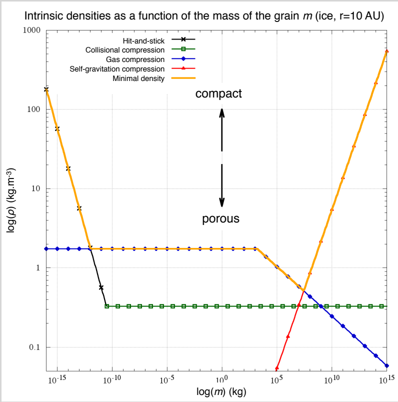
$\phi \sim 0$: highly porous grain

$\phi = 1$: compact grain

☞ Spherical grains with mass m and radius s



Kataoka et al.(2013b)



Static compression

$$\phi = \left(\frac{a_0^3}{E_{roll}} P\right)^{\frac{1}{3}}$$

Kataoka et al.(2013a)

a_0 : monomer size

E_{roll} : rolling energy

P : compressive strength

(a) $\rho_{hs} \propto m^{-1/2}$

(b) $\rho_{coll} \propto m^{0}$

(c) $\rho_{gas} \propto \begin{cases} m^{0} & (s \leq 9\lambda/4) \\ m^{-1/14} & (s \geq 9\lambda/4) \end{cases}$

(d) $\rho_{sg} \propto m^{2/5}$

λ: gas mean free path

3 - DYNAMICAL MODELS

T-Tauri disc model

$M_* = 1\ M_\odot$ $M_{disc} = 0.01\ M_*$

$0.1 \leq r\,(AU) \leq 300$ AU

$T_g \propto r^{-3/4}$ $\Sigma_g \propto r^{-3/2}$

$T(1\ AU) = 197$ K $\alpha = 0.01$

Aerodynamical parameters

Stopping time τ

Epstein: $s \leq 9\lambda/4$

$$\tau_{Ep} = \frac{\rho_s\, \phi\, s}{\rho_g\, c_g}$$

Stokes: $s \geq 9\lambda/4$

$$\tau_{St} = \frac{4\, \rho_s\, \phi\, s^2}{9\, \lambda\, \rho_g\, c_g}$$

c_g: gas sound speed

Stokes number St

$$\mathrm{St} = \Omega_k \tau$$

Model for migration

Radial velocity:

$$\frac{dr}{dt} = \tau \frac{1}{\rho_g} \frac{dP_g}{dr} \qquad St < 1$$

$$\frac{dr}{dt} = \frac{1}{\tau} \frac{1}{\rho_g} \frac{dP_g}{dr} \frac{r^3}{G\, M_*} \qquad St > 1$$

Weidenschilling (1977)

Model for growth

Relative velocity between identical grains:

$$V_{rel}^2 = 2^{\frac{3}{2}}\, \mathrm{R_o}\, \alpha\, c_g^2 \frac{\mathrm{St}}{(\mathrm{St}+1)^2}$$

R_o: Rossby number for turbulent motions ($R_o = 3$)

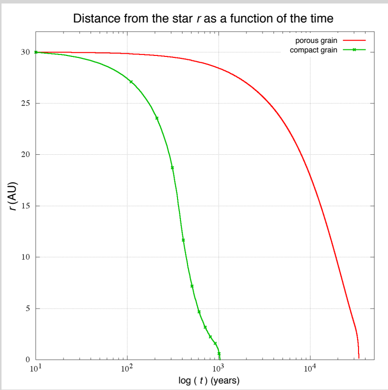
Temporal variation of the mass of the grain:

$$\frac{dm}{dt} = 4\,\pi s^2\, V_{rel}\, \rho_d$$

ρ_d: density of matter concentrated into SPH solid particles

Stepinski & Valageas (1996)

4 - ONLY MIGRATION



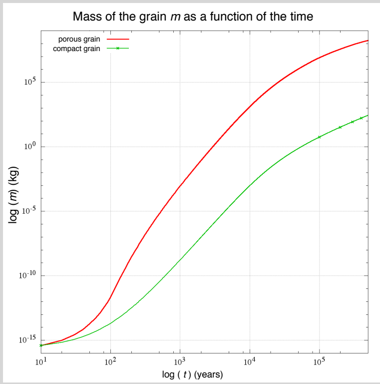
The migration is slowed down for a porous grain but in both cases, the grain is accreted

Initial conditions

Icy grains, $m = 1$kg

$r_i = 30$ AU

5 - ONLY GROWTH



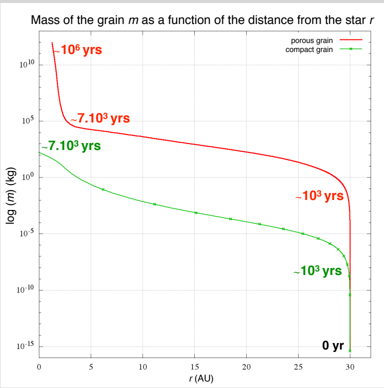
The growth is more efficient and quicker for a porous grain

Initial conditions

Icy grains, $s_i = 1\ \mu m$, $\phi_i = 0.1$

$r_i = 30$ AU

6 - MIGRATION & GROWTH



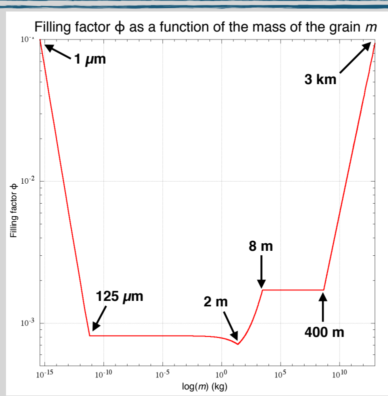
Porous grains grow faster and migrate slower, thus they can decouple from the gas and avoid being accreted

Porous grains keep growing close to the star to reach planetesimal sizes

Initial conditions

Icy grains, $s_i = 1\ \mu m$, $\phi_i = 0.1$

$r_i = 30$ AU



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The next step of our work will be to include the model for the evolution of porosity during growth in a modified version of the 3D SPH code of Fouchet et al.(2005)