Photophoresis effects in Protoplanetary Disks: a numerical approach

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Abstract: It is thought that rocky planets are formed in the inner regions of protoplanetary disks (PPD) about 1 - 10 AU from the star. However, it can be theoretically shown that when particles reach a size of about 1 meter they tend to be accreted very efficiently by the star. This is known as the radial-drift barrier. We explore the photophoresis in the inner regions of PPD as a possible mechanism for preventing the accretion of solids bodies onto the star. We include the photophoresis force in our two-fluid (gas+dust) SPH code in order to study its efficiency.

PHOTOPHORESIS IN A NUTSHELL

Photophoresis: thermal creep induced by the star's irradiation on a solid body due to the temperature gradient on its surface. The resulting force $F_{\rm ph}$ causes an outward motion of grains in PPD.

Empirical law:

$$F_{\rm ph} = \frac{2F_{\rm max}}{\frac{p_{\rm max}}{p} + \frac{p}{p_{\rm max}}}$$

low p	$F_{\rm ph} \propto p$
transition	$\max(F_{\rm ph})$
high p	$F_{\rm ph} \propto 1/p$

$$F_{\rm max} = \frac{a^2}{2} D \sqrt{\frac{\alpha}{2}\frac{I}{k}}$$

$$p_{\rm max} = \frac{3T}{\pi a} D \sqrt{\frac{2}{\alpha}}$$

$$D = \frac{\pi \bar{c} \eta}{2T}\sqrt{\frac{\pi\kappa}{3}}$$

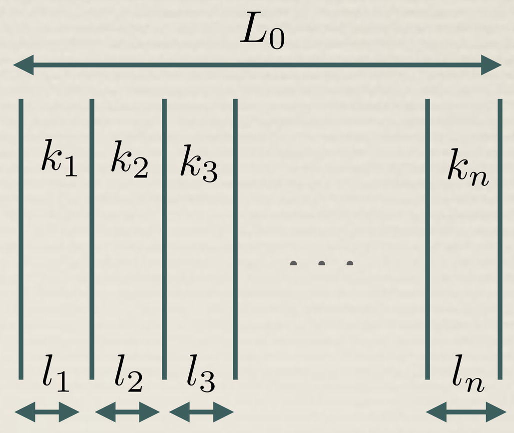
$$\bar{c} = \sqrt{\frac{8RT}{\pi\mu}}$$

$F_{\rm ph}$ depends on the radiant flux density I, the conductivity of the grain k, its cross section a^2, the thermal accommodation coefficient α, the viscosity of the gas η and the thermal creep coefficient κ.

Duermann et al. (2013)

CONDUCTIVITY & POROSITY

Consider a grain made of n alternate layers of gas and dust:



its conductivity is $k = \frac{L_0}{\sum_{j=1}^{n} l_j/k_j}$

introducing the porosity $P = l_{\rm void}/L_0$

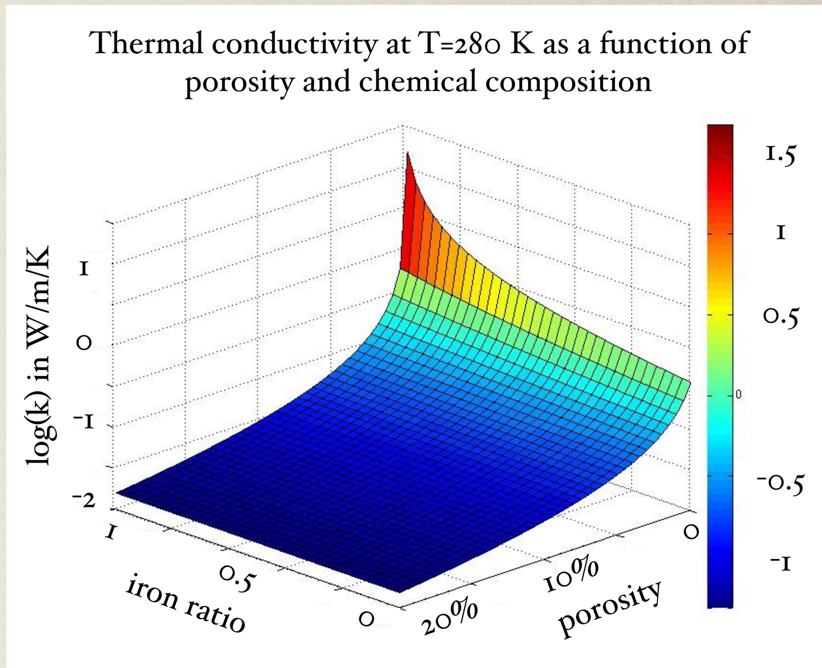
$$k = \frac{k_d k_g}{P(k_g - k_d) + k_g}$$

measured by *Opeil et al (2012)*

Conductivity inversely proportional to the porosity

Parameters
- porosity: [0,20%]
- chemical composition : iron/silicate ratio [0,1]

1) **Strong dependence on porosity**
2) Given a small porosity, weak dependence on composition.



NUMERICAL SIMULATIONS

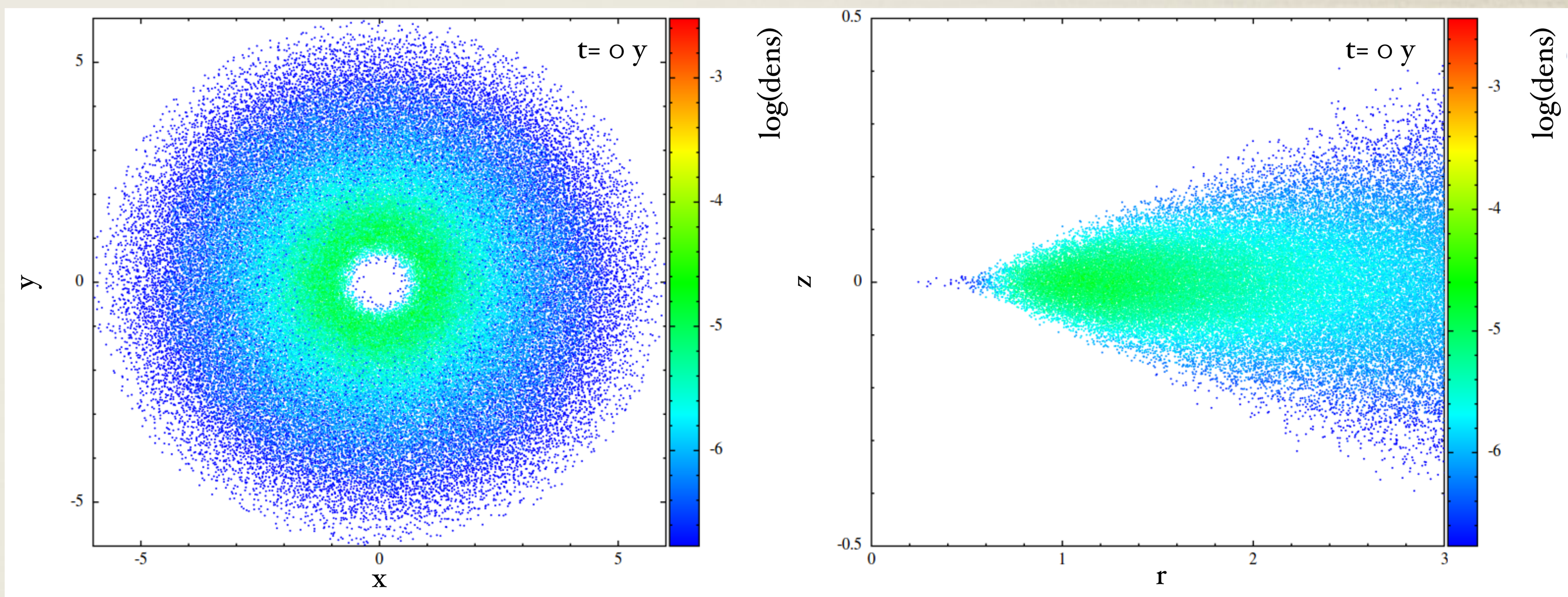
Disk model:
Minimum Mass Solar Nebula *(Hayashi 1985)*
zoom in the [0.1-5] AU disk
disk mass = 0.003 M_* .

$$T(R) = T_0(R/R_0)^{-1/2}$$
$$P(R) = P_0(R/R_0)^{-3.25}$$
$$T(1\,{\rm AU}) = 280\,{\rm K}$$
$$P(1\,{\rm AU}) = 1.3\,{\rm Pa}$$

Simulations parameters:
200.000 SPH particles
$\{\alpha_{\rm SPH} = 0.1,\ \beta_{\rm SPH} = 0.2\}$
10 cm grains with $\rho = 3.2$ g/cm3
th. conductivity $k = 0.1$ W/m/K

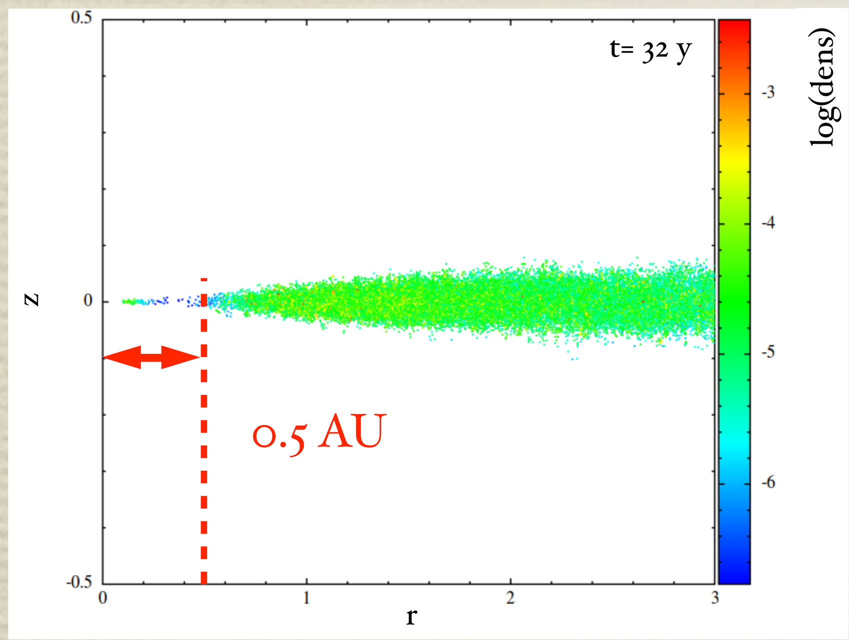
Uniform distribution at t=0 for gas and dust particles.
NB: the gas does not evolve much

INITIAL STATE



Evolution time = 30 years i.e. 30 orbits at 1 AU

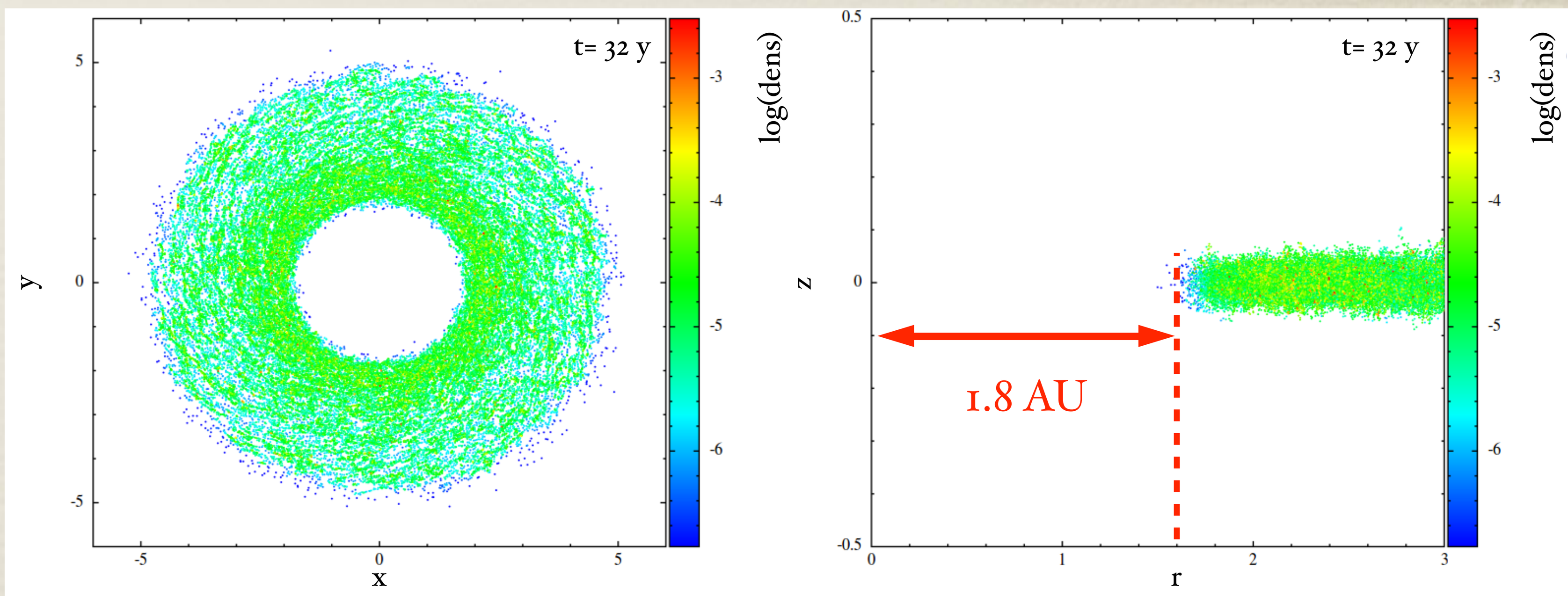
WITHOUT PHOTOPHORESIS



Gravity, drag, photophoresis and pressure forces computed

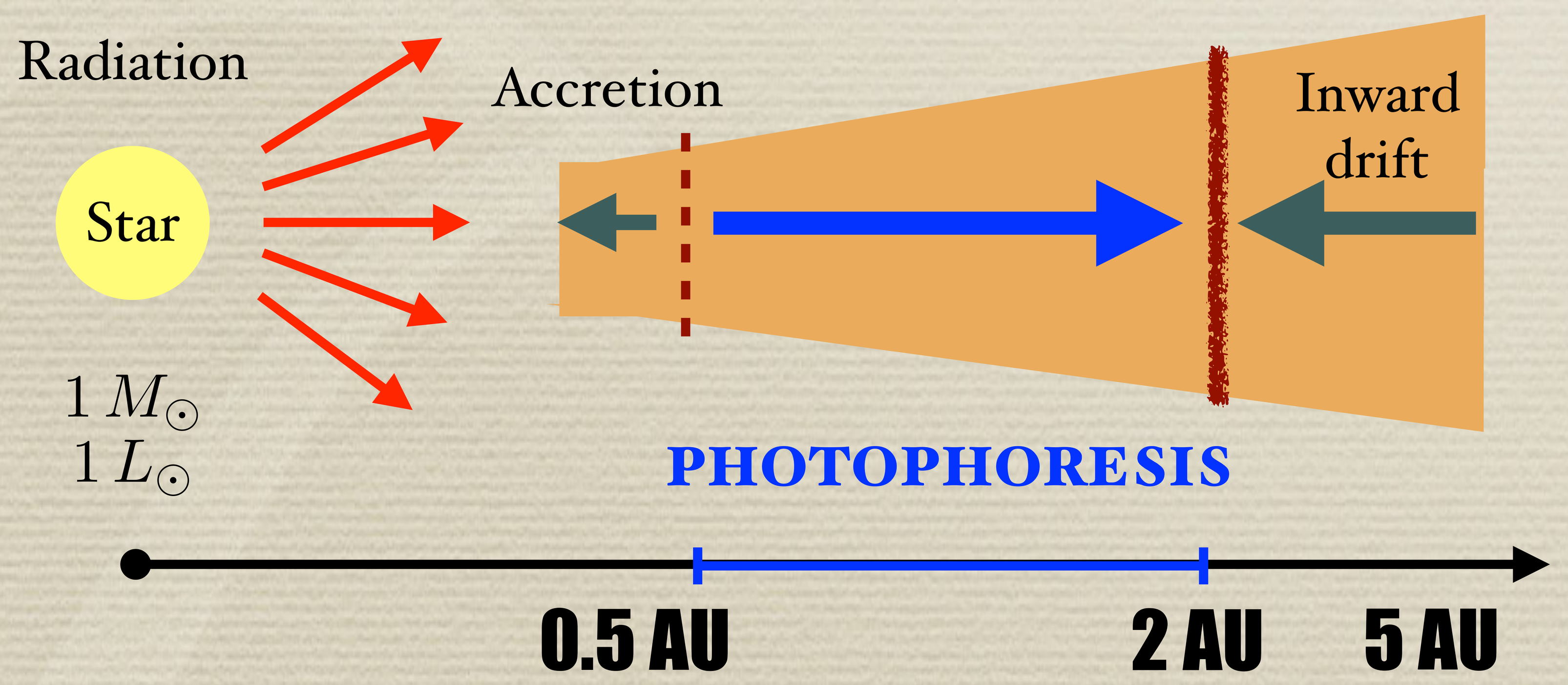
The particles located between 0.5 and ~ 2 AU move outward while particles beyond 4 AU move inward

WITH PHOTOPHORESIS



SPH code used: *Barrière-Fouchet et al. (2005)*

DISK SKETCH



CONCLUSIONS

The outward motion of the inner grains and the inward drift of the outer ones result in an accumulation zone.
The location of the inner rim depends on grain size, chemical composition and porosity.

Promising way to break the radial-drift barrier

REF:
Barrière-Fouchet et al. ; 2005, A&A, 443, 185
Duermann, C., Wurm, G., Kuepper, M. ; 2013, A&A, 558, A70
Hayashi et al. ; 1985, in Protostars and Planets II, 1100-1153
Opeil et al. ; 2012, Meteoritics and Planetary Science 47, 3, 319