TRANSPORT OF SOLID MATERIAL IN DYNAMICALLY EVOLVING 1D DISK MODELS WITH PRESSURE MAXIMA

Dóra Tarczay-Nehéz[1], Zsolt Regály[2], Zsolt Sándor[3]

[1] Department of Astronomy, Eötvös Loránd University, Hungary
[2] Konkoly Observatory, Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences, Hungary
[3] Department of Astrophysics, University of Vienna, Austria

Context

Planet formation theory based on the core-accretion scenario suffers from the very fast loss of dust particles, the building blocks of planetesimals. Thus, the available material to build planets is consumed before a significant mass of dust are able to stick together. An effective solution to this problem might be a pressure trap.

The radial drift of the dust particles are caused by the difference in the orbital velocity of the gas and the dust particles. At the edges of the accretionally dead zone in a protoplanetary disk (Gammie, 1996), the gradient of the gas pressure vanishes serving a trap for dust particles under inward drift. The increased density of dust particles there may accelerate the formation of planetesimals, and by subsequent collisions even the formation of planets and planetary cores.

In the present work we investigate the mass growth due to the dust particle accumulation in pressure maxima. Our results support the idea of rapid planet formation via core-accretion, but we find that the efficiency of dust accumulation depends on the disk physical parameters.

Viscously evolving disk model in 1D

To investigate the formation and viscous evolution of pressure maxima, we developed a time-dependent 1D hydrodynamic disk model using the α-prescription of Shakura & Sunyaev (1973). In this model, the dead zone is modeled by decreasing the effective viscosity α which describes the efficiency of the angular momentum transport in the disk.

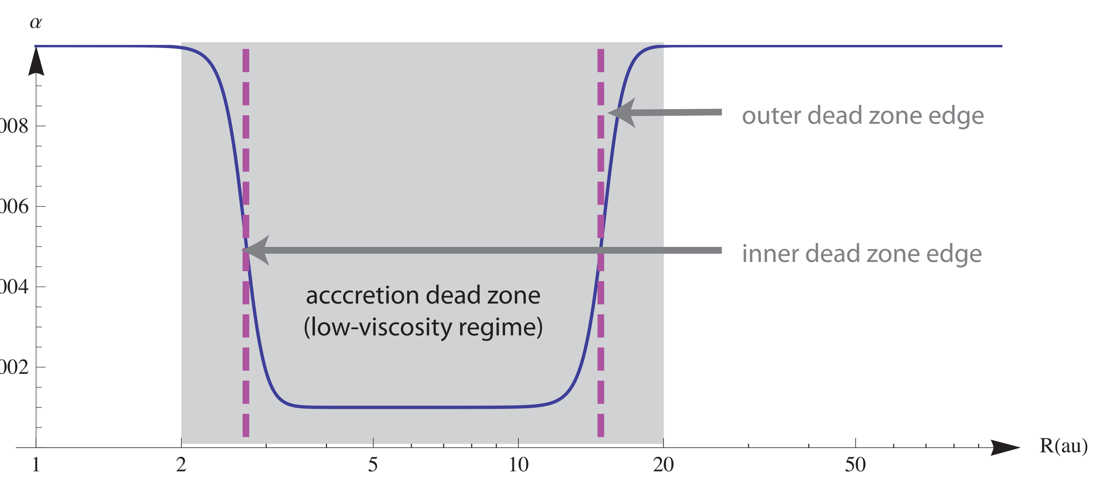
The diffusion equation describing the evolution of the surface density (Lynden-Bell & Pringle, 1974) in the axisymmetric case is given by

$$\frac{\partial \Sigma_{\rm g}(R,t)}{\partial t} = \frac{3}{R}\frac{\partial}{\partial R}\left[R^{1/2}\frac{\partial}{\partial R}\left(\nu(R)\Sigma_{\rm g}(R,t)R^{1/2}\right)\right],$$

where $\Sigma_{\rm g}(R,t)$ is the surface mass density of the gas at R radial distance from the central star and $\nu(R) = \alpha c_{\rm s}(R)H(R)$ is the kinematic viscosity of the gas (in the α-prescription). Here $c_{\rm s}(R) = H(R)\Omega(R)$ is the local sound speed, $H(R)$ is the pressure scaleheight of the disk measured from the midplane, $\Omega(R) = \sqrt{GM_*/R^3}$ is the Keplerian angular frequency, M_* is the mass of the central star and G is the gravitational constant (set to $G = 1$ in our simulations).

In the flat disk approximation $H(R) = hR$, while in the flaring case $H(R) = hR^{\gamma+1}$, where h is the aspect ratio and $\gamma = 2/7$ is the flaring index (Chiang & Goldreich, 1997).

To model the decline of the viscosity in the dead zone, α is smoothly reduced at the dead zone edges as shown in the Fig. below. We note that we placed the inner viscosity reduction to the radial location of the snowline, which in our case is at 2.7 AU.



Dust drift model

Due to the difference of velocity of the gas and the dust particles (i.e., the the velocity of gas is sub-Keplerian, while the velocity of the particles are Keplerian), each particle suffers deceleration resulting in inward radial drift. To model the radial drift, a simple 2-body model including the drag force was used. To solve the equations of motion of the 2-body problem we used a 4[th] order Runge–Kutta integrator.

The equations of motion of the dust particles in Cartesian (x, y) coordinates including the acceleration due to drag force, $f_{\rm D}(R)$ can be written as

$$\frac{d\mathbf{r}^2(t)}{d^2t} = -G\frac{M_* + m_{\rm p}}{|r(t)|^3}\mathbf{r}(t) + f_{\rm D}(R),$$

where $\mathbf{r} = \sqrt{x^2 + y^2}$ is the distance of particles to the central star, $m_{\rm p}$ is the mass of the dust particles and $f_{\rm D}(R)$ is the drag acceleration, which is calculated according to Lyra et al (2009).

Investigated disk models

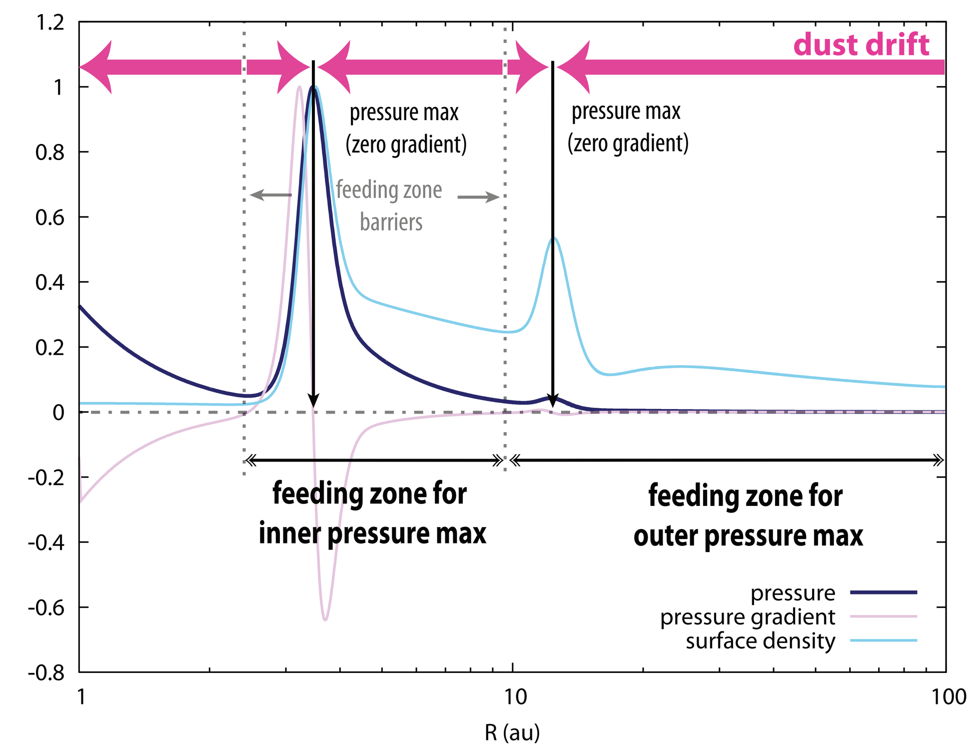
Combining the 1D hydrodynamic and the 2D dust drift model, we investigated both the flat and flaring disk approximations with different initial mass density profiles: $\Sigma_{\rm g}(R,0) \propto R^{-0.5}, R^{-1.0}, R^{-1.5}$. The accumulation of the dust at pressure maxima was investigated using different radius for the dust particles: $a = 1$, 5, 10, and 20 cm. The mass of the gas was set to $0.01 M_\odot$ and 1% of it was the mass of the dust. The 2D computational domain extended from 1 to 100 au consisting 10000 annuli. Particles were placed in each annulus with randomly selected azimuthal positions. In this way, to each dust particle the mass of the corresponding annulus was assigned.

The growth rate of the pressure maxima depends on the width of the region where the viscosity is reduced. For sharp dead zone edge width vortices form via Rossby-wave instability, for which cases the 1D axisymmetric approach is invalid. Therefore, we only investigated models in which the width of the dead zone edges are twice of the local disk scaleheight, $\Delta R_{\rm dze(i,o)} = 2H_{\rm dze(i,o)}$.

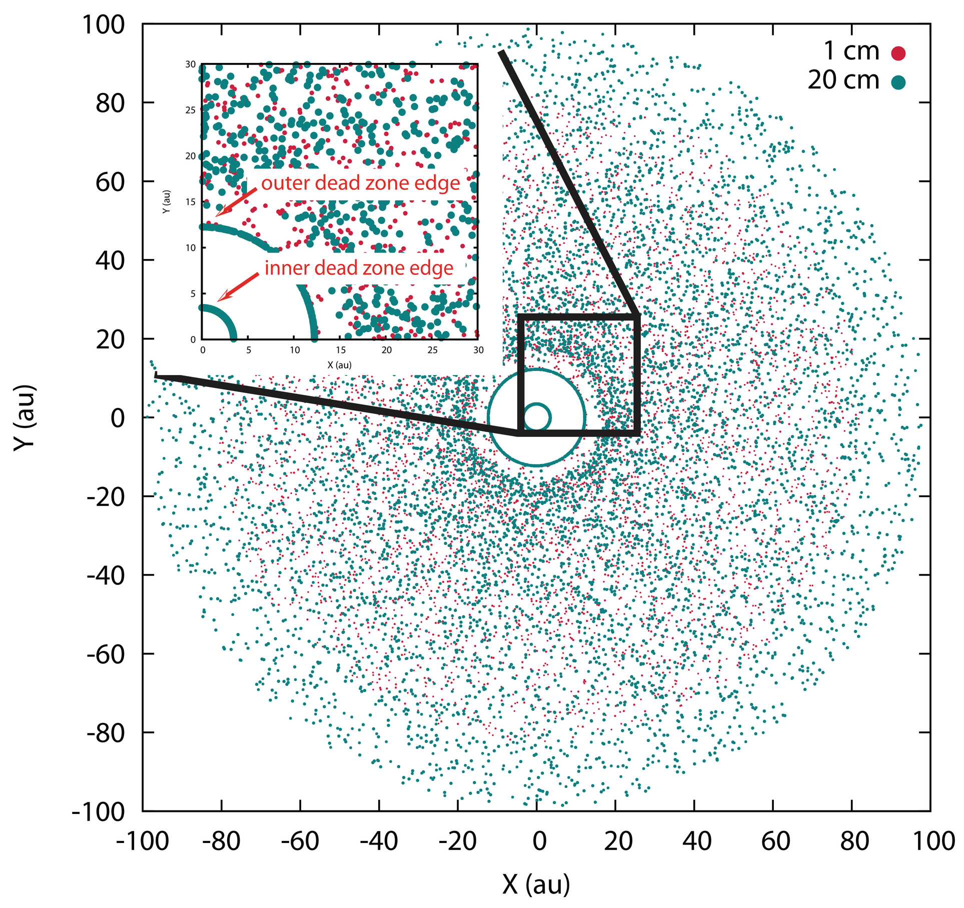
Dust drift with evolving pressure max

The viscous evolution of the disk and the radial drift of dust particles with a given size were followed to 10×10^3 yr. Both at the inner and outer viscosity transitions the gas is accumulated and pressure maxima formed. Since the drag force vanishes where the pressure has a zero gradient, dust particles are accumulated there. Negative pressure gradient results in a rapid inward drift of dust particles, while at positive pressure gradients the gas is super-Keplerian occuring outward drift of dust particles.

As a result, both the inner and the outer pressure maxima have a dust feeding zone. The inner pressure maximum is fed by the dust orbiting beyond the first pressure minimum and inside the second pressure minimum. However, the outer pressure maximum is fed by all the dust particles orbiting beyond the second pressure minimum. Thus, the feeding zone of the outer pressure maximum is the entire outer disk. The feeding zones for the pressure maxima are presented in the Fig. below.



Due to the viscous evolution of the disk, the inner pressure maximum shifts outwards, while the outer pressure maximum shifts inwards. As a result, the radial extension of the "feeding zones" for the pressure maxima evolves in time. Since the dead zone itself serves as the feeding zone for the pressure maxima, its dust content vanishes. As a result, all the particles initially orbiting inside the dead zone are accumulated in either the inner or outer pressure maxima, see Fig. below.

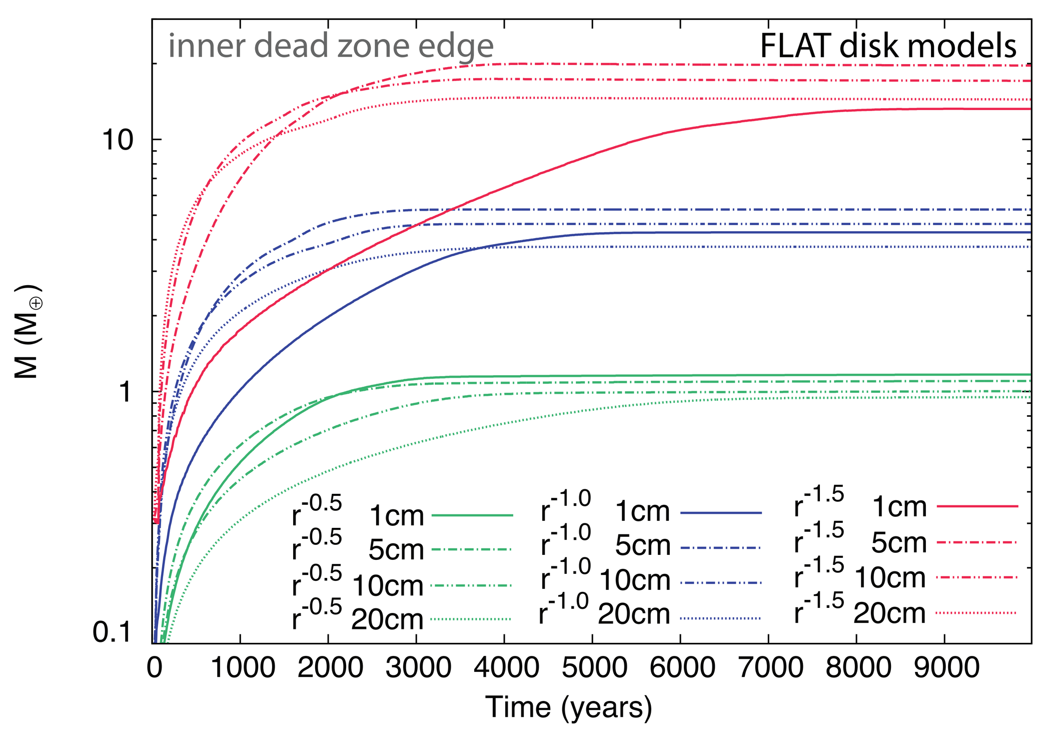


Since the drift rate of dust particles depends on the particle size, and the viscous evolution of pressure maxima depends both on the initial density profile and the scaleheight of the disk, it is worth investigating the dependence of the mass accumulation rates of dust particles at pressure maxima on the disk and particle properties.

Dust accumulation at dead zone edges

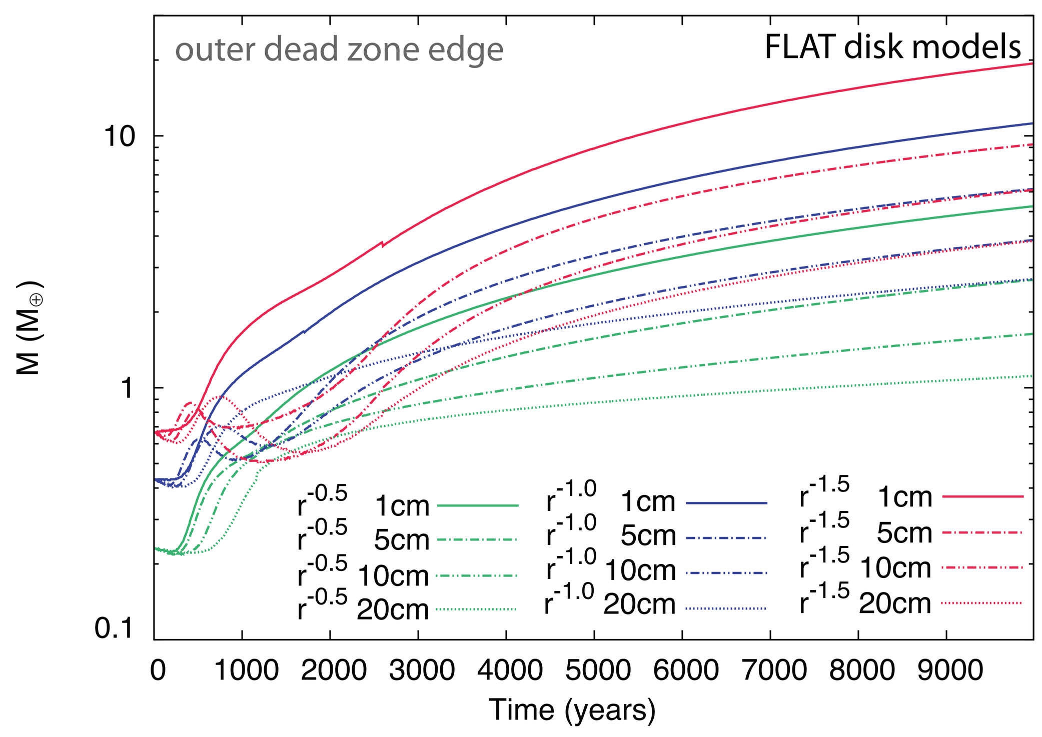
Following the dust drift with viscously evolving pressure maxima to 10^3 yr, we calculated the amount of dust accumulated at the dead zone edges. We did simulations to investigate how the dust accumulation depends on the disk initial density profile and size of dust particles.

In a flat disk model, the dust accumulation saturates at the inner dead zone edge within $\sim 2 \times 10^3$ yr, independent of the disk's initial density profile and the size of dust particles, see Fig. below.



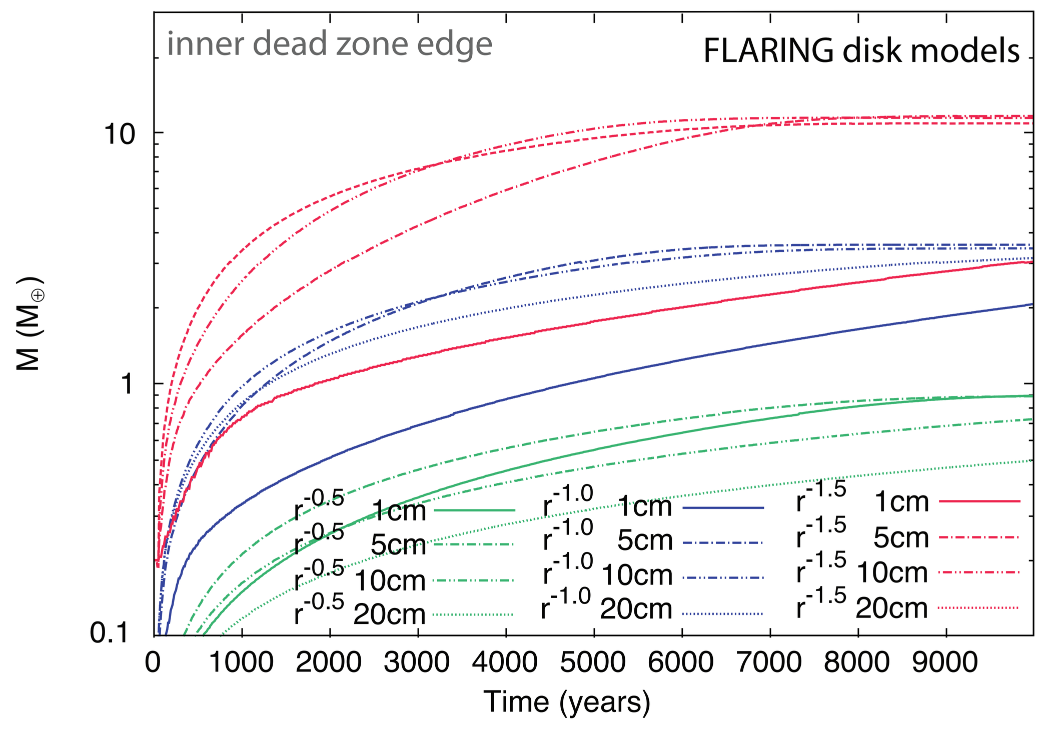
We found that the steeper the initial density profile, the larger the dust mass accumulated at the inner dead zone edge. Although a weak dependence of saturation mass on the size of dust particles can be observed for a given steepness of the initial density profile, the amount of dust accumulated at the inner dead zone edge is $\sim$ 10, 4 and $1 M_\oplus$ for -1.5, -1.0 and -0.5 power law index of initial density profile, respectively. For initial density slope of -1.5, the smallest saturation mass can be observed for the smallest particle size, however, with decreasing initial density slope, the minimum saturation mass shifts to larger dust sizes.

For the outer dead zone edge, the mass saturation happens in longer time-scale, thus within 10×10^3 yr of simulation, the overall mass growth rate shows no saturation, see Fig. below. Similarly to the inner dead zone edge, here the largest amount of mass accumulated at the end of the simulation occurs for models assuming the steepest initial density slope ($\Sigma_{\rm d} \sim R^{-1.5}$).

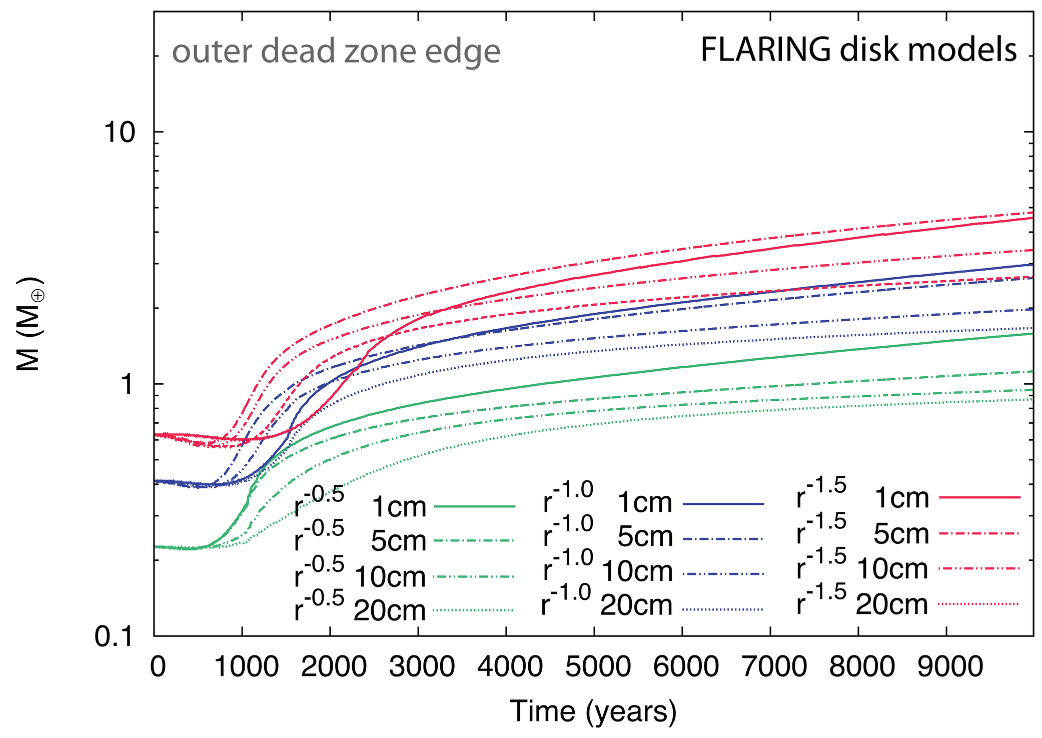


We found that the mass growth rate is always larger for the smallest dust particles, contrary to the growth rates observed for the inner dead zone edge. It can be explained by the fact that getting farther away from the central star, the smaller particles become more sensitive to the drag force.

In the flaring disk approximation we found that the mass growth rate of dust at the inner dead zone edge is much smaller compared to that of in flat models, thus saturation occurs at $t > 8 \times 10^3$ yr. The dependence of saturation mass on the initial density slope is similar to that of in flat models, however, the dependence on the dust particle size is much smaller, see Fig. below. The amount of mass accumulated is nearly the same as in the flat models.



Similarly to the flat disk models, dust mass saturation in flaring disk models is also not apparent for the outer dead zone edge to 10×10^3 yr. However, the dust growth rate shows a slightly clearer dependence on the initial density profile compared to the flat models. Note that the growth rate of dust mass is significantly lower for flaring disk.



Conclusions

In our simulations including the radial drift of non-interacting representative particles and viscous evolution of the pressure maxima formed at the dead zone edges, we found the followings:

1.) The growth of dust mass rate is saturated within 10×10^3 yr at the inner dead zone edge independent of the steepness of the initial density profile and the disk geometry being flat or flaring.

2.) The amount of dust accumulated at the inner dead zone edge can be as high as $\sim 10 M_\oplus$ for $\Sigma_{\rm d}(R,0) \propto R^{-1.5}$ and as low as $\sim 1 M_\oplus$ for $\Sigma_{\rm d}(R,0) \propto R^{-0.5}$ within 10×10^3 yr independent of the disk geometry.

3.) The steeper the initial density profile, the larger the amount of dust can be accumulated at the inner dead zone edge.

4.) With increasing inital density profile, faster growth rate happens for the larger dust particles.

5.) Contrary, the largest growth rate of dust mass in the outer dead zone edge occurs for the smallest dust particles.

In summary, our results show that the efficiency of planet-formation via core-accretion can be increased significantly by the pressure maxima formed at the dead zone edges, where even $\sim 10M_\oplus$ dust can be accumulated within several thousand years.

References and acknowledgement

Chiang, E. I. & Goldreich, P. 1997, *ApJ*, **490**, 368.
Gammie, C. F. 1996, *ApJ*, **457**, 355.
Lynden-Bell, D. & Pringle, J. E. 1974, *MNRAS*, **168**, 603.
Lyra, W.; Johansen, A.; Klahr, H.; Piskunov, N. 2009, *A & A*, **493**, 1125.
Shakura, N. I. & Sunyaev, R. A. 1973, *A & A*, **25**, 337.

This project has been supported by the Lendület-2009 Young Researchers' Program of the Hungarian Academy of Sciences.

More information at d.nehez@astro.elte.hu