Evolution of solids in the Jovian subnebula

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CONTEXT

During the late stages of envelope accretion of the Giant Planets, the angular momentum of the infalling gas prevents it from being accreted directly onto the planet and it must proceeds through an accretion disk [1]. It is within such a disk surrounding Jupiter, generally referred to as a subnebula, that the Galilean satellites Io, Europa, Ganymede and Callisto are thought to have formed [2]. However, neither the structure of the disk, nor the origin and size of the solids that eventually formed the satellites are currently constrained. To better understand the conditions of formation of the Galilean satellites, one must rely on the observational constraints so far available. The strongest of these constraints is the gradient in the water content of the moons [3]. Io is indeed completely dry, while ~ 8% of the mass of Europa is water and Ganymede and Callisto are made of half water half rocks.

In this context, we are developing a numerical model to track the evolution of solids of different sizes in the subnebula of Jupiter. The solids interact with the gas through drag forces, causing them to drift towards Jupiter or be entrained with the gas, and turbulent diffusion. During their evolution the solids are also heated by the surrounding gas and their ice sublimates. We thus are adding sublimation in order to track the ice-to-rock ratio of the solids as a function of time and position in the subnebula.

MODEL

The evolution of the density of solids is given by the advection-diffusion equation, which along any given direction in Cartesian coordinates reads [4]:

$$\frac{\partial \rho_p}{\partial t} + \frac{\partial}{\partial x}\left(\rho_p v_p - \rho_g D_p \frac{\partial}{\partial x}\left(\frac{\rho_p}{\rho_g}\right)\right) = 0$$

ρ_p, v_p, D_p : density, velocity and diffusivity of solid particles

ρ_g : gas density

This equation is solved in 3D using a Monte-Carlo particle tracking method. The position of particles subjected to the different transport processes is calculated over time. The new position of a given particle after a time step dt is then [5]:

$$x_i = x_{i-1} + v_{adv}\Delta t + R\left[\frac{2}{\sigma^2} D_p \Delta t\right]^{\frac{1}{2}}$$

R, σ^2 : a random number and the variance of the random distribution

$$v_{adv} = \frac{D_p}{\rho_p}\frac{\partial \rho_g}{\partial x} + \frac{\partial D_p}{\partial x} + v_{p,x}$$

The velocity $v_{p,x}$ is obtained by integration of the equation of motion of the particle :

$$\frac{d\vec{v}_p}{dt} = -\frac{GM_{Pl}}{r^3}\vec{r} - \frac{1}{t_s}(\vec{v}_p - \vec{v}_g)$$

t_s : stopping time of the particle, i.e., characteristic time for gas to transfer angular momentum to the particle

NOTION OF TRACERS

When solving the advection-diffusion equation with a particle tracking algorithm, i.e. a Lagrangian approach, an important notion to understand is that of tracers. The particles whose motion is calculated at each time step are in fact tracers, meaning that they actually represent an ensemble of solids sharing roughly the same size and position within the disk.

In order to conserve the mass of the system each tracer is given a fixed mass budget M_t. This mass budget is defined by $M_t = M_T/N_t$, where M_T is the total mass in solids of the disk and N_t is the number of tracers used in the simulation. This way, a tracer has a physical meaning and can be easily converted into solids' mass. The number of actual solid particles represented by one tracer is not fixed and may evolve with time. It is defined as $n_p = M_t/m_p$, where m_p is the mass of one solid. This number is not fixed because when sublimation of ices or collisions are added in the simulation, the mass of the particles represented by the tracer evolves. Note also that n_p needs not be an integer but that a significant number of tracers should be used to properly solve the equation and to provide meaningful statistics. Here we generally used at least 10^4 tracers.

RADIAL MOTION

Without Gas Drag

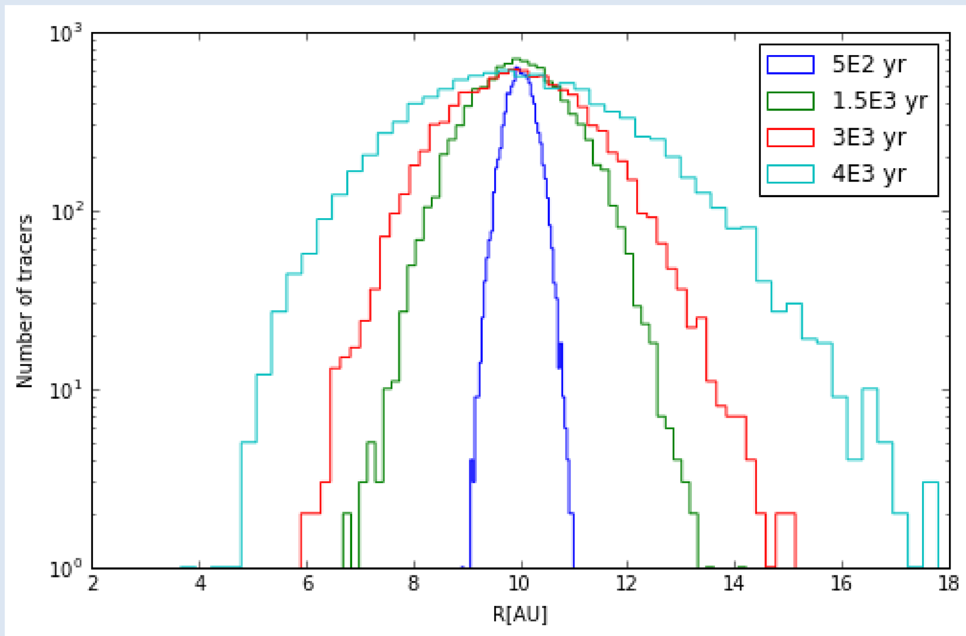

Figure 1. Diffusion of solid particles at the midplane of the disk without gas drag effects. 10^4 tracers were used, representing particles with a radius of 10^{-6} m. Note the asymmetry in the diffusion because of the gas density gradient.

With Gas Drag

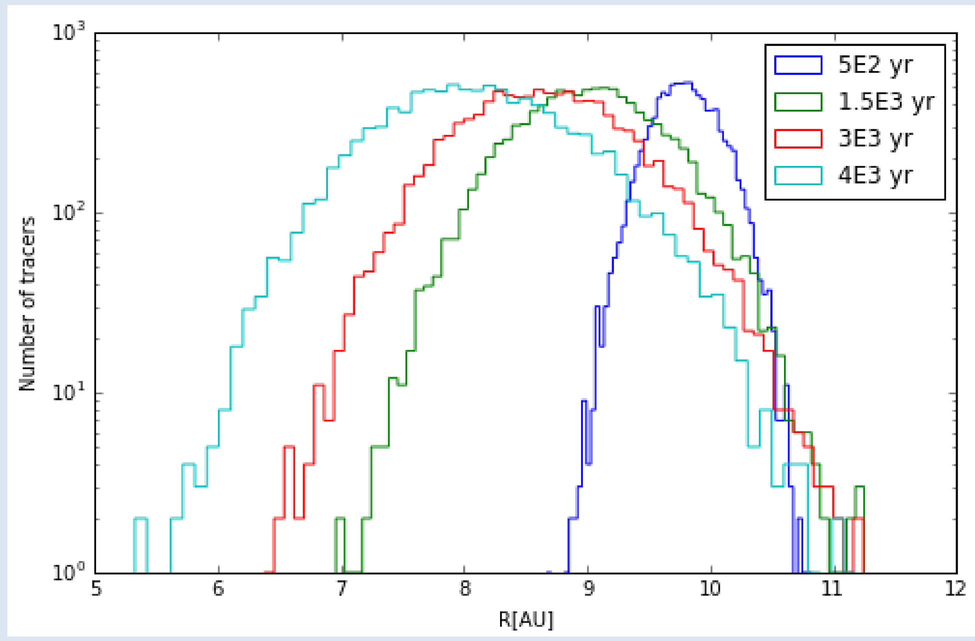

Figure 2. Same as figure 1 but with gas drag included in the simulation. The diffusion is still asymmetric but the collective behavior of particles is also clearly identifiable.

VERTICAL MOTION

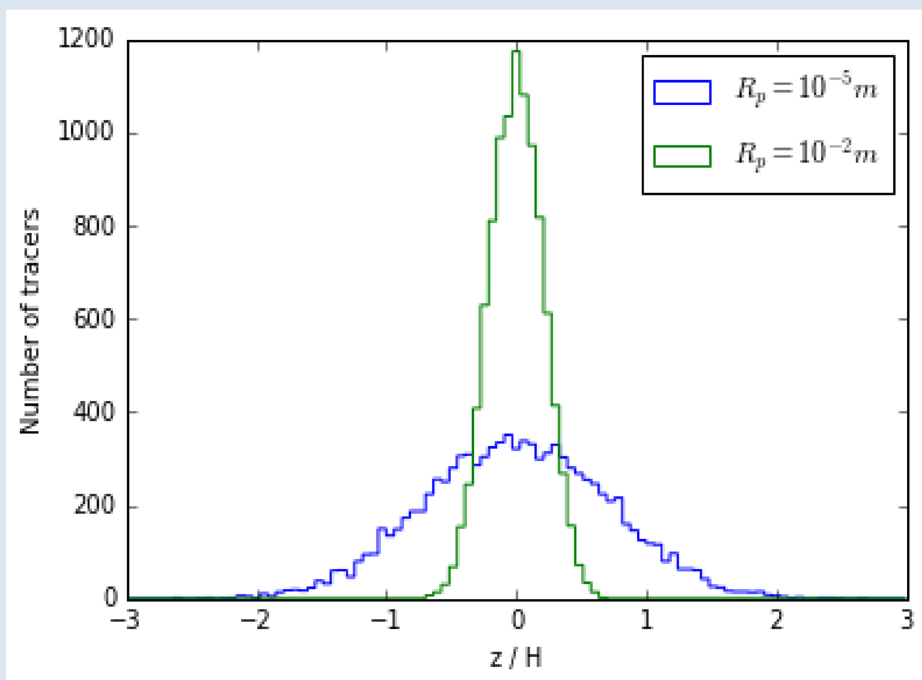

Figure 3. Settling of particles of different sizes. The simulations were run for 3×10^3 years with 10^4 particles. All particles were initially released at the midplane and evolved due to turbulent diffusion. The height z of the particles is normalized with the gas disk scale height H. The corresponding particles' scale height are $h_p \sim 0{,}7\,H$ and $h_p \sim 0{,}2\,H$ for particle sizes $R_p = 10\ \mu m$ and $R_p = 1\ cm$ respectively. Smaller particles are more tightly coupled with the gas and turbulent diffusion prevents them from being efficiently settled.

CONCLUSION & PERSPECTIVES

Here we present the first results of our simulation that includes several transport processes to describe the motion of solid particles within accretion disks. As we show, transport is influenced by gas density and particle size. Although not shown here, diffusion strongly depends on the level of turbulence as well.

The results presented are just the first step of this study. The aim is to track the ice-to-rock ratio of the particles during the lifetime of the subnebula ($\sim$1 My). To do so we are currently adding a module to determine the surface temperature of the particles and calculate the sublimation rate of water ice.

References

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