Tracking dust at the disk midplane: Implications for STARDUST

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Introduction:

With the relatively recent discoveries of more than 200 planets orbiting stars beyond our Sun, the study of planet formation has taken many steps forward. However, gaining a strong understanding of the planet formation process in extrasolar systems, as well as in our own solar system, is dependent on an understanding of the solid material available within circumstellar disks. We now know that things are not as simple as a planet forming in place only from the material in its immediate vicinity.

While planets may move within the disk as they form, it is also possible that solids and ices may also experience radial transport before being incorporated into larger bodies, effecting such things as the distribution of available water within the disk. Some clues as to the distribution and transport of disk solids do exist in planetary compositions, but also in observations of protoplanetary disks around other stars as well as the compositions of so-called "pristine" bodies, such as comets, believed to remain unaltered since their formation.

Of particular interest are crystalline silicates, high temperature minerals which are believed to have formed in the inner regions of the disk, but which have been found to exist in comets, both spectrally and with sample return via the STARDUST mission. These observations suggest significant outward transport of solids during the very early evolution of our solar system. As a specific reference point, STARDUST workers found a high temperature grain believed to have formed in the inner solar system 20 μm in size in samples from a comet believed to have formed beyond the orbit of Neptune [1].

Here we present simulations of dust particle transport at the midplane for two models of midplane gas radial velocity. Our model takes into account grain size as well as a disk viscously evolving in time. While a common approach by other authors is to model the dust and gas as two fluids, our model instead tracks a sample of individual dust particles within the gas disk environment.

Model:

We model dust motion at the midplane of a 1D, vertically isothermal model disk that is viscously expanding and accreting onto the parent star. We include the effects of photoevaporation by the central star as modeled by [2], which clears the disk over the course of a few 10^5 years once accretion has dropped to a few 10^{-10} $M_\odot$ yr^{-1}. Two extremes of disk gas radial velocity are calculated

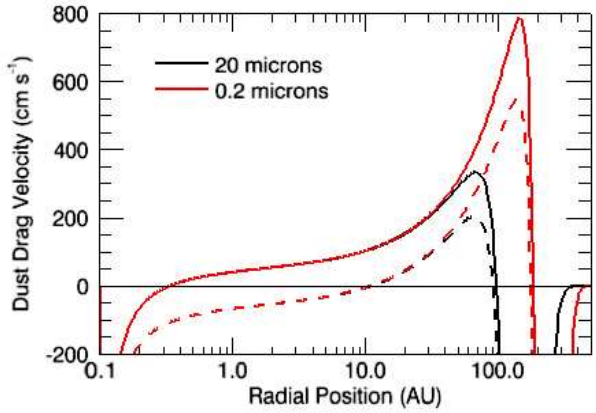

Figure 1: Dust particle drag velocities for two particle sizes in an example disk at t = 0. Solid lines correspond to simulations using the meridional gas velocity at the midplane and dashed lines to those using the gas accretion velocity.

by considering the net accretion flow of the gas and by modeling the meridional gas flow at the midplane as discussed by [3]. Meridional flow is often radially outward at the midplane. Simulations are run for each gas velocity case. The disk is modeled assuming a fixed temperature distribution with a radial dependence of $r^{-1/2}$ and $T(1AU) = 278.9$ K (corresponding to a gas scale-height of 0.0333 AU).

The dust is modeled as an initial distribution of particles in the inner disk that is then evolved forward in time as the disk evolves. The motion of the dust particles is governed by two effects: gas drag and turbulent diffusion. The motion due to gas drag is found by calculating a grid of dust radial velocities, taking into account the gas velocity and density at the midplane, as well as the dust particle surface-area-to-mass ratio. Figure 1 plots this dust radial velocity for two particle sizes at $t = 0$ of a standard model disk. Particle motions calculated in this manner compare well to direct Runge-Kutta numerical integration of particle trajectories.

The turbulent diffusion of the particles is modeled as a random-walk overlain onto the dust drag trajectory, assuming a diffusion constant of $D = \nu/Sc$, where ν is the local disk gas viscosity, and Sc is the Schmidt number including considerations of particle size as defined by [4]. For the particle sizes run $Sc \approx 1$, except where

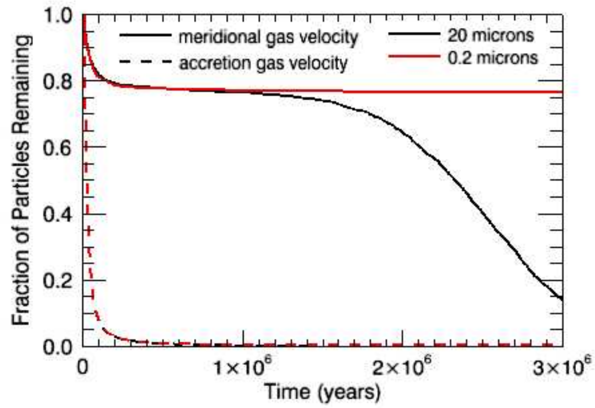

Figure 2: Fraction of particles remaining on the grid over time in an example simulation for two different particle sizes. Runs using meridional gas velocity begin with 2000 particles. Runs using accretion gas velocity begin with 10,000 particles.

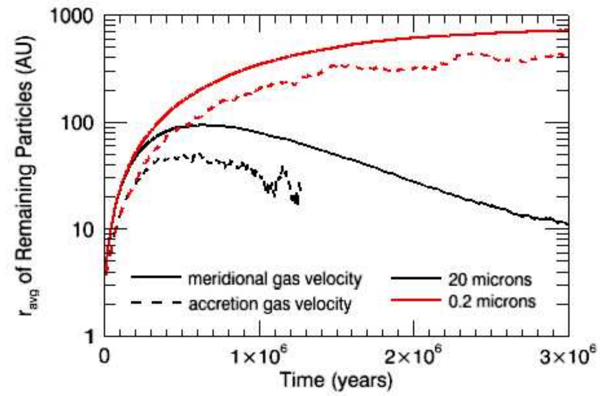

Figure 3: Average radial position of particles remaining on the grid in an example simulation. Particles are initially evenly distributed between 0.5 and 7 AU.

the gas density is exceptionally low, such as at very large radial distances or at late times in the disk evolution.

Preliminary Results:

Preliminary analysis of our simulations shows that some fraction of particles initially in the inner disk will be transported to large radial distances on timescales of a few 10^5 years. Though certainly not all transport of dust particles will take place at the midplane, depending on the flow patterns of the disk, dust may be largely outwardly advected or may only reach large distances due to upstream diffusion of particles. Figures 2 and 3 plot an example of the number of particles that remain on the grid over time and their average radial location in the disk for two particle sizes (assuming an intrinsic density of 3 g cm^{-3}) and both gas flow cases.

Our simulations suggest that outward transport of dust particles will not occur for the entire disk lifetime, but is generally limited to the early disk history. In the case of inward only gas flow, the fact that our model does not supply a source of dust at $t > 0$ means that all particles are eventually lost past the inner grid boundary and are not available for outward diffusion at late times. However, in the case of meridional gas flow, the gas disk surface density eventually drops to such a low that the flow will no longer support outward advection of dust grains despite the fact that the gas continues to flow outward at the midplane. As would be expected, this transition occurs earlier for the larger particle sizes, so that larger particles from the inner disk never reach such large radial distances as the smaller particles and are lost inward sooner.

In the case of the STARDUST particle mentioned above, 20 μm is a relatively large particle size for these simulations, however some outward transport of these particles to comet-forming regions is still expected. Early outward transport coupled with later in-fall may provide time-constraints for the formation of larger bodies in these regions.

Our model assumes that the disk temperature structure is constant in time, however it is expected that a disk will be hotter than average early in its evolution, when crystalline silicates are likely forming. Therefore, some other factors that we would like to examine for their effects on dust transport include the disk temperature, as well as the initial disk mass configuration.

References: [1] Brownlee D. et al., Science 314, 1711-1716 (2006); [2] Alexander R.D. & Armitage P.J., M.N.R.A.S. 375, 500-512 (2007); [3] Takeuchi T., Lin D.N.C., ApJ. 581, 1344-1355 (2002) [4] Youdin A.N. & Lithwick Y., Icarus 192, 588-604 (2007);