**TRACING SOLIDS AND VAPOR DURING PARTICLE GROWTH: COMMUNICATION BETWEEN THE MIDPLANE AND SURFACE LAYERS IN A PROTOPLANETARY DISK.** S. Krijt[1] and F. J. Ciesla[1], [1]Department of the Geophysical Sciences, The University of Chicago, 5734 South Ellis Avenue, Chicago IL 60637 (Email: skrijt@uchicago.edu)

**Introduction:** Protoplanetary disks around young stars serve as analogs for our own solar nebula, the cloud of dust and gas that circled the Sun after its formation and provided the raw materials for constructing the planets. A major issue in developing our models for planet formation is reconciling the astronomical observations of protoplanetary disk surfaces with meteoritic materials which presumably were sampling the solar nebula midplane. Differences in gas densities, temperatures, and photon fluxes would lead to differences in the physical and chemical evolution of materials in these environments. It is thus critical to understand not only how efficiently materials mix from one region to the other, but also how materials are processed and altered during transit.

Materials at the disk surface will be brought down to the disk midplane via a combination of diffusion and gravitational settling, while midplane materials can be lofted to the disk surface by diffusion. Here we extend the particle-tracking methods developed by [1] to explore how particle growth affects the ability of small grains to be transported from these different regions in the disk. We also explore how the vertical transport of grains leads to the vaporization/freeze-out of water ice on more refractory solids and the impact this has on the water vapor distribution in the disk.

**Particle Growth:** The vertical distribution of solids of a given size in a disk is described by the scale-height of the solid distribution, $h_d$, which is found by balancing the upward diffusive flux with the downward flux due to gravitational settling. For very small particles that are well coupled to the gas, $h_d \sim h_g$, where $h_g$ is the scale-height of the gas. This implies that small particles will be distributed at a constant (small) dust-to-gas ratio throughout the height of the disk.

The consideration outlined above assumes that the distribution of solids is controlled by the two processes described. However, interactions with other particles has thus far been ignored. Small particles can collide with other solids and stick, forming increasingly larger aggregates. As these aggregates grow larger in size, their aerodynamic properties change, resulting in more efficient settling and less diffusion. This would lead to solids concentrating at the disk midplane, enhancing the dust-to-gas ratio locally, while depleting the dust from the disk surface layers.

Collisions between dust aggregates can also result in fragmentation or disruption, liberating small particles allowing them to again follow paths that have them strongly coupled to the gas. These fragmenting collisions are the primary source of small grains in more evolved protoplanetary disks and are necessary to explain the observed abundance of small grains in such systems [2].

While the coagulation of dust aggregates has been investigated previously [2-5] to determine the vertical distribution of particles as a function of size, we have developed a method to examine how individual particles are transported through the vertical height of the disk [6]. We use the particle-tracking methods of [1] to follow the dynamics of a given dust grain. Assuming a steady-state dust distribution as described by [5], for every displacement step a particle experiences, we determine a collision probability with the background dust distribution. When a collision occurs, we randomly select with which sized particle the grain collides. If the collision is deemed to be accretional, the dust grain is incorporated into a corresponding larger aggregate. If a collision occurs that results in fragmentation, we track one of the fragments, randomly chosen from the size distribution resulting from the collision. We then follow the dynamics and collisional history of the collision product, repeating the dynamical-collisional procedure.

Figure 1 shows the background dust population taken from the dust growth models of [4] used in our calculations. Here we consider a region of the disk at 5 AU, a gas surface density of 180 g/cm$^2$, a vertically-integrated dust-to-gas mass ratio of 0.01, a turbulent parameter of $\alpha=10^{-3}$ and a fragmentation velocity of 5 m/s. Figure 2 shows the dynamical and collisional lifetime of one of our tracked particles. The particle begins as a 0.1 μm grain at the disk midplane. Almost immediately, the monomer is incorporated into a larger grain, and in less than 1000 years finds itself in a grain ~1 mm in size. Over the 20,000 years of simulation, the monomer spends most of its time in objects of this size or larger, only occasionally being released as a small fragment as a result of an energetic collision. The lifetime of the small grains is short though (especially in the dense midplane), and it does not take long before the grain is incorporated into a larger aggregate again.

The large fraction of time spent in large bodies combined with the relatively short durations spent as a small grain limit the ability for the monomer to diffuse to high altitudes in the disk. Having run a large number of similar calculations, we find that for those bodies released at the disk midplane, all small particles (those which should be well coupled to the gas) have distributions with scale heights of $h_d \sim 0.7 h_g$, or 30% less than predicted when collisions are not taken into account. The discrepancy is greater in areas of low turbulence and high dust-to-gas ratios. Thus, transport of fine particles from the midplane to the disk surface is less efficient than previously recognized.

**Ice Sublimation/Freeze-out:** We are also exploring how the vertical distribution of volatiles in the gas phase may be affected over regions of condensation fronts. In passive protoplanetary disks, the lower temperatures and higher densities at the disk midplane would lead to volatiles, like water, freezing out onto grains while remaining as a gas in the lower density, warmer regions closer to the atmosphere that are heated by incident radiation from the star. Vapor may diffuse downward to freeze-out near the disk midplane, while being replenished as dust grains diffuse to the disk surface and desorb volatiles. The volatile abundance at the disk surface will be determined by the balance of these two processes.

We have begun exploring this issue by expanding our approach, allowing water molecules to desorb from/adsorb onto grains as they move through a vertical slice of the disk. Frozen out molecules then move with the grains that they adsorb onto, while molecules in the gas are diffused throughout the vertical extent of the disk, with their concentration tracked as a function of height.

The vapor concentration in the upper altitudes of a disk is intimately tied to the dynamical and collisional evolution of the dust at lower altitudes. As grains grow, fewer are lofted to heights where the water can desorb and return to the gas. As a result, water vapor concentrations would be depleted in regions of significant grain growth and settling. High vapor concentrations could then imply lack of dust growth/settling, or the absence of a condensation front at the disk midplane. Such depletions have been inferred for the surfaces of the ~10 Myr old disk TW Hya where a significantly evolved dust population is expected [7].

**Discussion:** The methods we have developed here show how both solids and volatiles are transported between the disk midplane, where meteorites formed, and the disk surface which is what is seen in astronomical observations. Such information is critical for finding ways of linking the data for these two fields as we can evaluate how processes operating in one region impact what is seen in another.

**References:** [1] Ciesla F. J. (2010) *ApJ, 723,* 514 [2] Dullemond C. P. and Dominik C. (2005), *A&A, 491,* 663 [3] Weidenschilling S. J. (1997), *Icarus, 127,* 29 [4] Ciesla F. J. (2007), *ApJ, 654,* L159 [5] Birnstiel T., Ormel C. W. and Dullemond C. P. (2011), *A&A, 525,* A11 [6] Krijt and Ciesla (2016), *ApJ, in prep.* [7] Du F., Bergin E. A., and Hogerhijde M. R. (2015), *ApJ, 807*, 32.

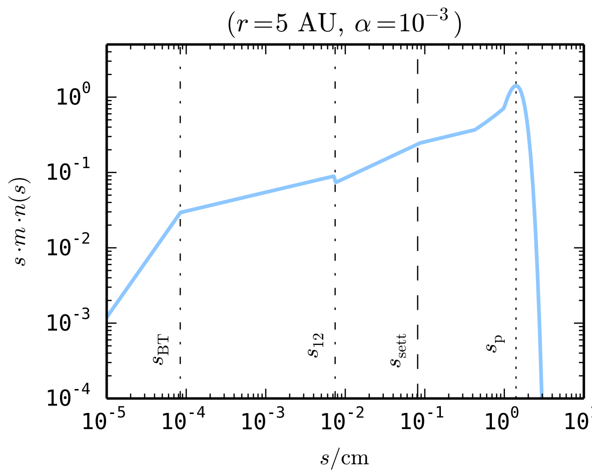


Figure 1: Normalized steady-state dust size distribution resulting from fragmentation-limited growth at 5 AU assuming a fragmentation velocity of 5 m/s. The largest aggregates, those with sizes ~1 cm, dominate the solid mass budget.

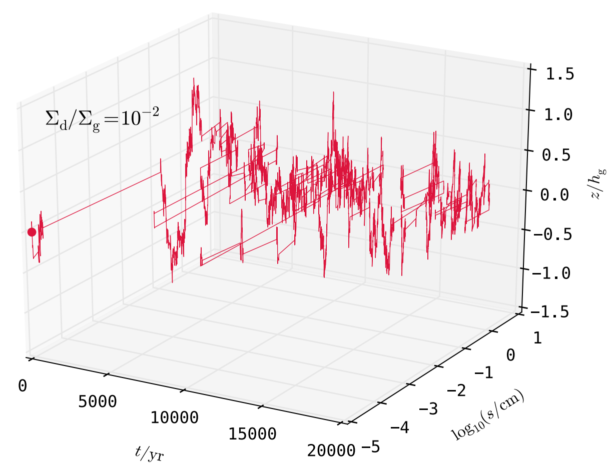


Figure 2: Simulated history of a 0.1 μm grain released at the midplane of a typical protoplanetary disk experiencing settling, diffusion and collisions with other aggregates. During the simulated 20,000 years, the monomer spends most of its time inside large mm- to cm-size aggregates and in a region relatively close to the disk midplane.