RADIAL TRANSPORT OF HIGH TEMPERATURE MATERIALS IN THE SOLAR NEBULA: APPLICATIONS TO STARDUST.

F. J. Ciesla[1] and J. N. Cuzzi[2], [1]Carnegie Institution of Washington, Department of Terrestrial Magnetism, 5241 Broad Branch Road NW, Washington, DC 20015 (ciesla@dtm.ciw.edu), [2]NASA Ames Research Center, MS 245-3, Moffett Field, CA 94035 (jcuzzi@arc.nasa.gov).

Introduction: Among the most startling findings of the Stardust mission is the large number of samples that contain minerals that formed at high temperatures in the solar nebula [1]. These high-temperature minerals include forsteritic olivine as well as an object whose mineralogy is similar to the Calcium-Aluminum Rich Inclusions found in chondritic meteorites. The temperatures required to form these minerals are not expected to have been present in the extreme outer regions of the solar nebula where comets are expected to have formed. These findings suggest that large-scale radial transport must have operated in our protoplanetary disk, moving materials outwards from the hot inner regions of the solar nebula, to the outer regions where they were incorporated into the bodies that formed there.

A number of mechanisms have been proposed for transporting materials outward in protoplanetary disks. Among them are: bipolar outflows, possibly launched from the X-point [2,3], convection and gravitational torques in a gravitationally unstable disk [4], and diffusion caused by turbulence [5]. Each of these mechanisms is likely to transport materials outwards at different times during the evolution of the protoplanetary disk, on different timescales, and through different paths, implying that there should be differences in the thermal, chemical, and accretional evolution that bodies would experience depending on the mechanism responsible for their outward transport. We are beginning an investigation to understand how the different transport mechanisms differ in terms of efficiency of outward transport and the alteration that may occur along the paths that particles would take during their outward treks. Here we focus on how small particles are transported outwards in weakly turbulent protoplanetary disks.

Outward Transport in Protoplanetary Disks: The outward transport of solids in protoplanetary disks is thought to be hindered by the inward drift caused by two sources: advective flows in an evolving disk and gas drag. The advective flow of a disk is expected because protoplanetary disks are observed to evolved through the inward transport of mass which is then accreted by the central star [6]. Gas drag is a result of the expected generally outward pressure gradient at the midplane of protoplanetary disks, which causes the gas to orbit the central star at sub-Keplerian rates. As a result, solids experience a headwind in their orbit which causes them to lose energy and momentum to the gas and migrate inwards with time [7].

The rates at which the advective flow and gas drag carry materials inward will depend strongly on the physical structure of the disk, with the radial pressure gradient and disk viscosity being most important. Not surprisingly, the value of the pressure gradient varies with location. What is not generally appreciated is that the radial pressure gradient will *switch signs* approximately one scale-height above the disk midplane. This results in the gas at these heights orbiting at super-Keplerian rates, which produces a tailwind on solids in the disk and will cause them to migrate *outwards* [e.g. 8,9] While such an effect would not be important for large bodies ($a > \sim 10$ cm), as they would settle to the disk midplane where the pressure gradient is negative, this effect may be important for small particles such as crystalline grains and refractory inclusions which can be lofted to high altitudes by turbulence.

Model: We have developed a model to track the paths taken by the particles of various sizes through a protoplanetary disk. We are investigating a variety of disk structures and evolutionary stages. The particles originate at some location (r_0, z_0) and are transported due to: gas drag, advective flows (when the disks are evolving), gravitational settling, and turbulence when present (modeled as a random walk). We are currently using the model to track the dynamical evolution of swarms of particles in order to develop transfer functions which describe the probability of a particle being transported from one location to another for various times. In addition, we are accumulating statistics on the various paths taken by the particles during transport as these paths will determine the different environments that the particles are exposed to and thus the chemical and physical alteration that they experience [10]. Comparison of these statistics with actual cometary and meteoritic samples will serve as tests to the model.

Figures 1 and 2 show preliminary results from our models which show the final radial location of dust particles after 1 million years in disks with $\alpha=10^{-3}$ and 10^{-4} respectively. These grains were assumed to have radii of 10 μm and were initially located at the midplane of the disk at 1 AU. The fraction of particles which survived in each case were 50% and 80% respectively. While more particles were lost to the sun in the $\alpha=10^{-3}$ case, those particles that survived were transported further outwards. In the $\alpha=10^{-3}$ case, ~22% of all grains were located outside of 20 AU at the end of the simulation, whereas none were found beyond that distance in the $\alpha=10^{-4}$ case. If comets formed beyond 20 AU, this implies that the solar nebula must have had, initially, $\alpha>10^{-4}$ if turbulent diffusion was responsible for the outward transport of high temperature materials.

Figure 3 shows the particular path for a single 10 μm grain in a disk with the $\alpha=10^{-4}$ over a period of 10^6 years. This grain is lofted away from the midplane and spends much of the time in low density environments and where it can avoid being incorporated into larger bodies which would hinder its outward transport. In fact, the time spent above a scale height (dotted lines in the graph) aids the outward transport of the grain because the radial pressure gradient of the gas is positive, allowing gas drag to push it further outwards. This may be the most effective way for high temperature materials to be transported outwards to where solids would form, and offers a possible way of sorting particles by size: small particles will remain lofted for longer periods of times, while larger particles will settle more readily. This will be investigated further.

Summary: We are investigating the efficiency and paths by which particles are transported outwards in protoplanetary disks. Unlike previous models, we are modeling transport in 2-D, rather than one, in order to account for variations in the radial transport rates with height above the disk midplane. The results of our models will be compared to Stardust results in order to constrain processes in the solar nebula.

References: [1] Brownlee D. *et al.* (2006) *Science, 314*, 1711-1716. [2] Shu F. H., Shang H. and Lee T. (1996) *Science, 271*, 1545-1552. [3] Liffman K. (2005) *MaPS, 40*, 123-1358. [4] Boss A. P. (2004) *ApJ, 616*, 1265-1277. [5] Cuzzi J. N., Davis S. S., and Dobrovolskis A. R. (2003) *Icarus, 166*, 385-402. [6] Calvet N. et al. (2005) *AJ, 129*, 935-946. [7] Weidenschilling S. J. (1977) *MNRAS, 180*, 57-70. [8] Takeuchi T. and Lin D. N. C. (2002) *ApJ, 581*, 1344-1355. [9] Haghighipour N. and Boss A. P. (2003) *ApJ, 598*, 1301-1311. [10] Cuzzi J. N. et al. (2005) *ASP Conference Series 341: Chondrites and the Protoplanetary Disk*. 732.

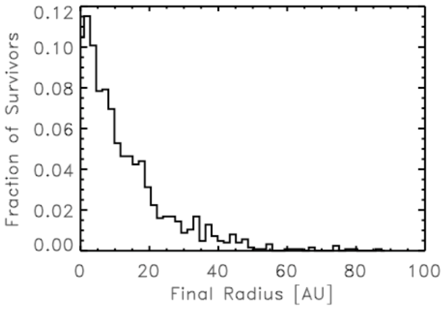

Figure 1: Histogram showing where test-particles are located after 10^6 years in a disk with $\alpha=10^{-3}$.

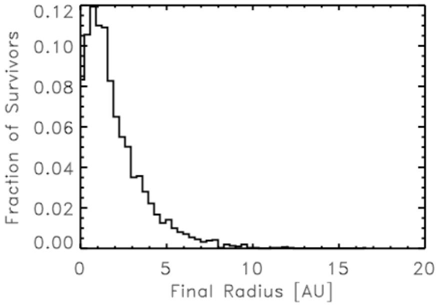

Figure 2: Same as Figure 1, but with $\alpha=10^{-4}$.

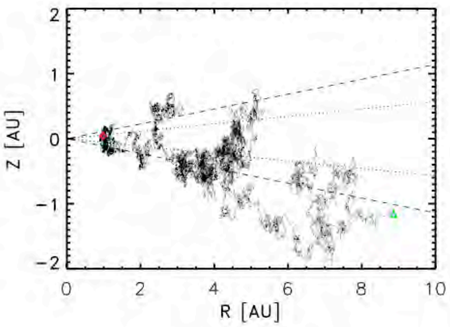

Figure 3: Example of the path of a single tracer particle in a protpoplanetary disk with $\alpha=10^{-4}$. The red diamond represents the starting position and the green triangle represents the position after 10^6 years. The dotted lines and the dashed lines represent the one and two scale height distances respectively.