A NEW APPROACH TO NEBULAR TRANSPORT MODELS: PARTICLE TRAJECTORIES. Fred J. Ciesla[1], [1]Department of Geophysical Sciences, The University of Chicago, 5734 South Ellis Avenue, Chicago IL 60430, (fciesla@uchicago.edu).

Introduction: The presence of crystalline silicates and refractory inclusions in the materials collected from comet Wild 2 by the Stardust spacecraft has been interpreted as evidence for the transport of solids from the hot, inner regions ($<\sim$3 AU) of the solar nebula to the cold, outer regions ($>\sim$20 AU) where comets origi-nate [1]. A number of models have been proposed to explain this observation [e.g. 2-7], with each being tied to the global evolution of the solar nebula. These same processes would also have served to transport the materials that were eventually accreted by the planets or meteorite parent bodies. Thus identifying the cause of this transport will help us understand the dynamic evolution of the nebula as well as the chemical evolution of the materials that formed the bodies throughout the solar system.

To date, models for transport have largely focused on showing that it is possible for materials to be car-ried from one region of the nebula to another. In some cases the relative fraction of high temperature materi-als in the comet formation region are calculated [3-5], or the level of homogenenization is determined by tracking how well mixed materials become with time [6,7]. While such quantitative analyses help to demonstrate the effectiveness of these models in their ability to transport or mix materials, they unfortunately cannot be used as predictions to be tested by our current data on primitive bodies. For example, it is unclear from the Stardust materials what fraction of material from Comet Wild 2 formed in the inner solar nebula due to the uncertainty in the amount of materials that was collected that escaped thermal processing prior to being accreted by the comet. Further, telescopic observations of comets result in estimates of the fraction of crystalline silicates they contain varying from comet to comet and from observation to observation for a single comet [e.g. 4], suggesting that even if such a number were known, it may not be representative of comets as a whole or of Comet Wild 2 individually. Thus, at present, the available data cannot conclusively argue in favor for, or rule out any, one model.

Here, a new approach to calculating the transport of solids throughout the solar nebula is explored. Rather than focusing on how the abundance of a species changes with time within the solar nebula, this approach focuses on the path that single particles take during transport. That path then can be used to determine what environments (e.g. pressures, temperatures, etc.) a particle was exposed to during transit, and how that particle would have been altered as a result. This predicted alteration can then be compared to the record of alteration seen in primitive materials and thus used to test models of particle transport in the solar nebula.

Numerical Methods: To begin with, the two-dimensional transport model of Ciesla [5,7] is considered. The motions of a particle are determined by calculating the velocities of the particle due to the large-scale flows, gas drag, and vertical settling (determining net V_r and V_z) and thus moving the particles some distance $\Delta r = V_r \Delta t$ and $\Delta z = V_z \Delta t$ where Δt is the timestep for the calculation. In all cases the focus is on small particles that are trapped to the gas (stopping times less than an orbital period) so assuming a steady-state velocity rather than calculating the detailed forces is valid. The large-scale flows of the disk are calculated using the analytic forms of [8], with the gas drag and settling velocities calculated using the expressions given in [9].

In the absence of diffusion, all particles that began at a given location would move together, winding up at the same final position at the end of the simulation. However, diffusion imparts random motions to each particle such that over time these particles diverge from one another and follow unique paths. To account for this, each particle is assumed to experience a random walk at each timestep, the magnitude of which is given by $0 < |\Delta r| < (\alpha c H)^{\frac{1}{2}} \Delta t$ (as the particles are well trapped to the gas) and whose sign is chosen randomly. A similar method is used for $|\Delta z|$. A similar approach was used in [10], but here the 2D dynamics of the disk are considered and the method follows the specific formulism of [11].

Application to CAI Dynamics: As a primary application of this new method of looking at nebular transport, the dynamical evolution of CAIs during the early evolution of the solar nebula was considered,. Here, 0.5 diameter particles were released in a model solar nebula with $\Sigma(r)$=4000(r/AU)$^{-\frac{1}{2}}$ g/cm^2 and $T(r)$=1000(r/AU)$^{-1}$ K at r=0.64 AU (T=1573 K) and z=0. Of those 1000 particles considered, 41 survived in the disk (did not migrate inside of 0.4 AU) for 200,000 years. The final positions of the surviving particles are ploted in Figure 1. For each of these particles, it is then possible to de-termine what path they took to migrate to their final positions. Figure 2 shows an example of such a path for the particle whose position at t=200,000 years is (r,z)=(1.85 AU, 0.11 AU), and is indicated by the red symbol in Figure 1. Prior to reaching its final position in this simulation, however, the particle experienced a random walk throught the inner nebula, migrating as far as $\sim$2.5 AU from the Sun, and ranging as far as 0.3 AU from the disk midplane. This resulted in the particle traveling through a range of temperatures and pressures (Figure 3).

A qualitative inspection of this particle trajectory indicates that multiple episodes of high-temperature (T>1500 K) processing would have occurred, with the particle moving in and out of regions of the nebula where melting and evaporation is expected to occur. This particular particle would most likely have the morphology of a Type B1 CAI as the timescale for evaporation of materials would be much less than the timescale of chemical diffusion due to the high pressures it was exposed to for extended periods of time [12]. Statistical analyses of these paths and the expected chemical evolution that would occur could help to constrain and test models of transport in the solar nebula.

References: [1] Brownlee D. et al. (2006) *Science*, *314*, 1711-1716. [2] Shu F. H., Shang H, & Lee T. (1996) *Science*, *271*, 1545-1552. [3] Gail H.-P. (2001) *A&A*, *378*, 192-213. [4] Bockelee-Morvan D. et al. (2002) *A&A*, *384*, 1107-1118. [5] Ciesla F. J. (2007) *Science*, *318*, 613-615. [6] Boss A. P. (2008) *Earth & Planet. Sci. Let.*, *268*, 102-109. [7] Ciesla F. J. (2009) *Icarus*, In Press. [8] Takeuchi T. & Lin D. N. C. (2002) *ApJ*, *581*, 1344-1355. [9] Tanaka H., Himeno Y. and Ida S. (2005) *ApJ*, *625*, 414-426. [10] Cuzzi J. N. et al. (2005) In *Chondrites and the Protoplanetary Disk*, 732-773. [11] Visser A. W. *Marine Ecol. Prog. Ser.*, *158* 275-281. [12] Richter F. M., Mendybaev R. A., & Davis A. M. (2006) *Meteorit. & Plan. Sci.*, *41*, 8-93.

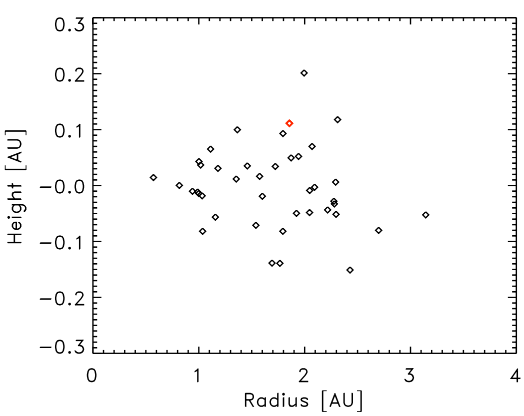

Figure 1: Final positions of the 41 (out of 1000) surviving particles released at (r,z)=(0.64 AU,0 AU) after 200,000 years.

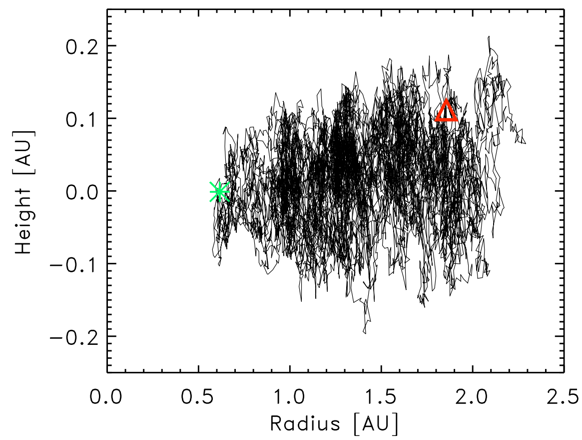

Figure 2: The path traveled, or space occupied, over 200,000 years by the particle whose final position is indicated by the red diamond in Figure 1. The starting position is indicated by the green asterisk and the final position by the red triangle.

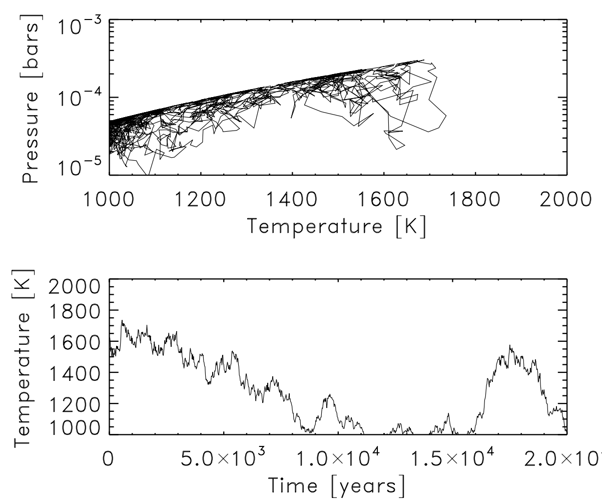

Figure 3: The path of the particle from Figure 2 in Pressure-Temperature space (top) and its thermal evolution as a function of time (bottom) for the first 10% of the simulation.