PARTICLE RESIDENCE TIMES IN SOLAR NEBULA ENVIRONMENTS: CHEMICAL EVOLUTION DUE TO RADIAL MOTIONS IN AN EVOLVING DISK.

F. J. Ciesla[1], [1]Department of the Geophysical Sciences, The University of Chicago, 5734 South Ellis Avenue, Chicago IL 60637, USA, fciesla@uchicago.edu.

Introduction: Models for the redistribution of materials in the solar nebula largely focus on tracking how the concentration of a tracer species (whether it be dust or gas) changes as a function of place and time [e.g. 1-5]. Such models (here called "dye-tracking" models) have demonstrated that the large-scale redistribution of materials in the solar nebula would have been a natural outcome of protoplanetary disk evolution, whether that evolution was driven by gravitational instabilities or turbulence. Such results are encouraging as they may explain the high-temperature materials found in comets and isotopic variations seen in primitive materials [1-5].

The picture that develops from these studies is that the early stages of planet formation involved a number of dynamical processes that led to the large-scale redistribution of materials within the solar nebula. During transport, solids would be exposed to a wide range of chemical and physical environments, which would vary with location and time in the evolving solar nebula. Such environments would be characterized by different gas pressures, temperatures, elemental abundances, and fluences of energetic particles and photons expected, each of which would have destroyed or altered solids to some degree. Thus, the properties of dust grains must reflect the integrated effects of each environment to which they are exposed and not just the conditions under which that grain first "formed".

As the generally used "dye-tracking" method of modeling transport in the solar nebula does not allow for such paths to be determined, a new approach is needed. Here we build on Ciesla (2010) [6], who developed a Monte Carlo model to describe the vertical motions of solids in a protoplanetary disk, and develop a model to study radial transport in an evolving solar nebula. A similar model has been used to explore the net results of transport similar to the "dye-tracking" method [7], though with a different computational approach. Further the focus here is understanding in detail how the properties of primitive materials are shaped by the path they take in the disk.

Monte Carlo Model: Ciesla (2010) [6] developed a Monte Carlo model to calculate the vertical motions of particles subjected to diffusion and gravitational settling in a turbulent protoplanetary disk. In addition to the motions arising from these processes, considerations were also needed to account for the vertical structure of the gas in the disk, as the flux of diffusing particles depends on the ratio of the density of the species to the density of the nebular gas, and for spatial variations in the diffusion coefficient. Here we apply the same techniques, but for the radial motions in a protoplanetary disk that evolves with time.

A validation test of the Monte Carlo model is shown in Figure 1, where the redistribution of particles released at 5.2 AU in an evolving solar nebula is calculated. The distributions of the particles are shown after 10^4, 10^5, and 10^6 years, with the solid line showing the distribution where the transport is modeled using the "dye-tracking" method, while the dashed lines represent the distributions of particles calculated using the Monte Carlo model developed here. The agreement between the different calculations gives confidence that the Monte Carlo models accurately describe the radial motions of particles in a protoplanetary disk.

Combining this model with the vertical model developed in Ciesla (2010) [6] allows us to begin exploring how the two-dimensional motions of materials in the solar nebula determined the conditions that particles are exposed to and the resulting chemical evolution that occurs. This differs from that used in [8, 9] in that a more accurate treatment of the Monte Carlo method is used, we are not limited to looking at steady-state accretion disks, and we no longer assume a vertically isothermal disk, allowing for thermal gradients that arise as dissipated energy diffuses to the disk surface.

One Application—Subsolidus Evolution of CAIs: The focus of radial transport models in recent years has centered on understanding how high-temperature materials from the inner solar nebula were transported outwards to be incorporated into comets [10]. Previous studies demonstrated that turbulence in an evolving disk could carry such grains outward [1,3-5,7], but Figure 2 shows the paths that such particles may take. Specifically Figure 2 shows the radial location of three individual particles over 10^6 years in a solar nebula initially described by $\Sigma(r)=7000(r/1\ \mathrm{AU})^{-1}$ g/cm^2 and evolving with a turbulence parameter of $\alpha=10^{-3}$. These particles originate at the outer edge of the isothermal (T=1350 K) cavity of the disk, above the condensation point of Mg-silicates and Fe-metal, where CAIs may form [11]. Each particle, while originating and finishing at nearly the same location, takes a unique path through the disk. The temperatures to which they are exposed are shown in Figure 3, demonstrating how particles that formed together in space and time can be processed differently as they are transported through the disk. Figure 4 shows the statistics of time spent above a given temperature for those high-T solids that survive for 10^6 years in the disk as in [9].

Discussion: Figure 4 provides quantitative information on the sub-solidus evolution CAIs in the solar nebula. A number of model runs have been performed to explore how variations in nebular parameters impact this thermal evolution. Diffusion profiles in CAIs suggest lifetimes above T~1200 K of $<10^4$ years [12], which most surviving CAIs achieve for a wide range of nebula conditions (i.e. Fig 4). Fe-zoning in spinel has been used to suggest that CAIs experienced T>~1000 K for decades to centuries [13], though this was for a single CAI. If this holds true for all CAIs (and is representative of the time immediately after the CAI left the globally high-T region of the nebula), this is most easily achieved in disks that evolve very rapidly (those with $\alpha \geq 10^{-3}$), constraining the initial rates of mass and angular momentum transport in the solar nebula. However, as discussed, data from a large number of CAIs are needed in order to understand the fraction of CAIs for which this constraint holds.

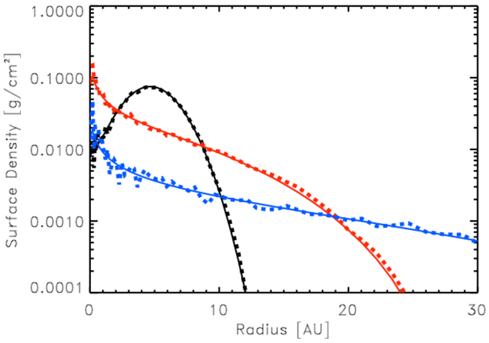

Figure 1: Comparison between the “dye-tracking” models for material transport (solid lines) and the Monte Carlo model developed here (dashed lines) in a viscously evolving disk with an initial surface density of $\Sigma(r)=7000(r/1\ \mathrm{AU})^{-1}$ g/cm^2. Materials were released into a disk at 5.2 AU with $\Sigma_0^{Trace}=1$g/cm^2. Model results at 10^4, 10^5, and 10^6 years are shown in black, red, and blue respectively.

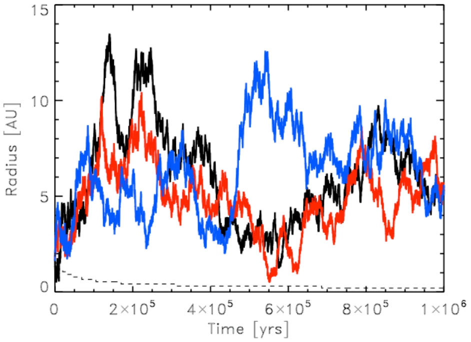

Figure 2: Radial location as a function of time of 3 CAI-like 1 mm solids, originating at T=1350 K at the beginning of same locations, the three particles take different paths through the disk. Dashed line at bottom of plot shows position of T=1350 K point in the disk.

Summary: The Monte Carlo model developed here allows us to quantify the types of environments particles are exposed to in the solar nebula and time spent in each. This allows chemical models to be combined with physical models for disk evolution and material transport. We continue to explore applications of this model to the chemical evolution of primitive materials, such as subsolidus vaporization and the formation of Wark-Lovering rims [11,14] or gas-solid reactions with known reaction rates [e.g. 15], and will present our most recent results.

References: [1] Cuzzi J. N. et al (2003) *Icarus, 166,* 385-402 . [2] Boss A. P. (2008) *EPSL, 268,* 102-109. [3] Ciesla F. J. (2007) *Science, 318,* 613-615. [4] Ciesla F. J. (2009) *Icarus, 200,* 655-671. [5] Ciesla F. J. and Cuzzi J. N. (2006) *Icarus, 181,* 178-204. [6] Ciesla F. J. (2010) *ApJ, 723,* 514-529. [7] Hughes A. L. H. & Armitage P. J. (2010) *ApJ, 718,* 1633-1653. [8] Ciesla F. J. (2009) *LPS XL,* Abstract #1099. [9] Cuzzi J. N. et al. (2005) *ASP Conf Ser. 341,* 732-773. [10] Brownlee D. et al (2007) *Science, 314,* 1711-1715. [11] Cassen P. (2001) *MaPS, 36,* 671-700. [12] Richter F. M. et al. (2006) *MaPS, 41,* 83-93. [13] Paque J. M. et al (2007) *MaPS, 42,* 899-912. [14] Wark D. (2005) *MaPS, 40,* 711-720. [15] Fegley B. (2000) *SSR, 92,* 177-200.

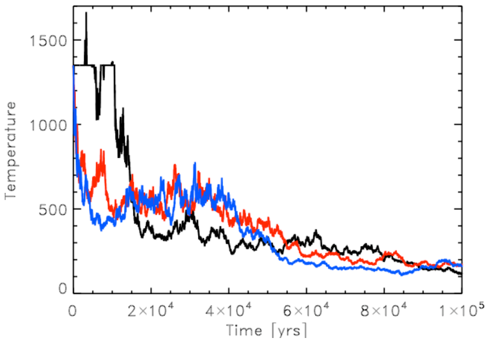

Figure 3: Temperatures that the three particles in Figure 2 see in the first 10^5 years of evolution in the disk. Note the difference length of time exposed to high temperatures.

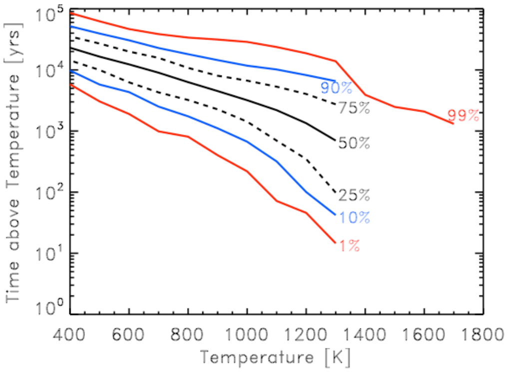

Figure 4: Probability Distribution Functions of particles released at T=1350 K in the viscous disk and how long they experience temperatures of a given value, integrated over their lifetime in the disk. This plot is read such that 99% of all particles see temperatures above 1700 K for less than 1000 years, and 10% experienced T>1200 K for <100 years.