A HIGH RESOLUTION MODEL OF WATER TRANSPORT IN AN EVOLVING PROTOPLANETARY DISK. F. J. Ciesla[1], [1]Department of the Geophysical Sciences, University of Chicago, 5734 South Ellis Avenue, Chicago IL 60637, USA, fciesla@uchicago.edu.

Introduction: Water transport in protoplanetary disks is important to understand for a variety of reasons. Among them, the concentration of water in the inner solar system is expected to have been critical in setting the redox state of the nebula [e.g. 1] as well as possibly have been important in changing the oxygen isotopic compositions of solids in the inner disk [2,3].

Ciesla and Cuzzi [4] presented a suite of simulations that examined how the distribution of water in a protoplanetary disk was impacted by disk evolution, radial diffusion, particle growth, gas drag migration, vaporization, condensation and planetesimal formation. Because of the array of processes considered, a number of simplifying assumptions were made in order to allow for the model to simulate timescales of millions of years—the amount of time over which chondritic materials were processed and thus the minimal time needed to be considered in such a model. Here we build on this previous model by considering a larger number of solid particle sizes in order to evlaute how the transport of solids, which depends sensitively on the sizes of the particles of interest, impacts the distribution of water in a protoplanetary disk.

General Evolution of the Water Distribution: The general pattern of behavior that developed in [4] (and discussed previously in [5]) was that water ice from the outer disk would coagulate into particles that were large enough to decouple from the gas and drift inwards under the influence of gas drag. As these icy bodies entered the hot, inner region of the disk, they would vaporize, locally increasing the distribution just inside of the snow line (as the flux of inward drifting of icy solids exceeded the outward drift of diffusing vapor). Over time, the outer disk became depleted in water ice, and that which remained got locked up in immobile planetesimals, decreasing the inward drift rate of water ice. At this point, the outward flux of diffusing vapor would be sufficient to begin depleting the inner disk of water, and resulting in continued dehydrating of the terrestrial planet region.

The magnitude of the variations in the water abundance in the inner disk and the timescale overwhich the above evolutionary phases lasted depended sensitively on the assumed rate at which icy particles grew and drifted inward with time. The Ciesla and Cuzzi model [4] considered only three sizes of solids: *dust, migrators, and planetesimals*, with dust being a portion of solids that follow the same dynamical evolution as the nebular gas, palentesimals being the portion that is large enough to decouple entirely from the gas and remain fixed at their location, and migrators are those that drifted inward through the disk due to gas drag. Each of these populations of solids were meant to account for the dynamical behavior of a wide range of solid particles. However, it remains untested how well the three categories of solids describe the detailed dynamical evolution of a population of solids that could span 12 orders of magnitude in size.

Model Modifications: We continue to use the α-viscosity model to describe the long-term evolution of a protoplanetary disk under the effects of mass and angular momentum transport. This model allows us to define the gas properties at any location in the disk, and as a result, determine the dynamical behavior of the water vapor or solids as a function of time and location.

Solids are broken up into 100 different size bins, with the smallest solid considered being 1 μm in radius, and each bin increasing in radius by a factor of 1.15, reaching an upper size of ~120 cm in radius. This upper limit is chosen as experimental studies suggest that collisional growth beyond ~1 meter in size is likely frustrated in protoplanetary disks as collisional velocities for particles of that size are likely so high as to result in fragmentation, rather than coagulation [6]. The transport of each type of solid is then calculated, by defining the size-specific diffusion coefficent [7] and the radial drift rates [8].

Dust growth is not explicitly modeled here, but instead, the mass of solids is assumed to always be distributed as a power-law. That is, after transport, the total mass of solids at a given location in the disk is calculated, and the amount of mass contained in particles of a given size is then distributed across the size bins of solids in a way to match the analytic form of the power-law. Such a form for the size distribution is supported by detailed studies of coagulation [e.g. 9], and indeed has been shown to be the natural distribution of solids in a system experiencing collisions that lead to both coagulation and fragmentation [10].

Planetesimal growth is assumed to operate on some timescale, t_{acc}, where the solids that are present in the disk are removed at a rate as given by [4]. This form of planetesimal growth mimics that advocated by Cuzzi et al [11], which suggests that solids in the disk can be locally concentrated into gravitationally bound clumps. Similar planetesimal formation mechanisms have been advocated by other authors [12,13].

An additional modification to the model is that it is able to track the dynamical evolution of multiple species within the disk. That is, Ciesla and Cuzzi (2006) examined the dynamical evolution of water throughout the disk, without regard to where it originated. However, the oxygen isotopic composition of water in the solar nebula may vary due to self-shielding in the nebular disk [2,14] or in its parent molecular cloud cre [3,15]. As such, it is necessary to understand how two different species, subjected to the same growth and transport processes, are redistributed within the disk with time. Thus, we can track up to 200 species of solids—100 size bins of 2 different compositions, with solids of "mixed" compositions being proportionally distributed between the two endmembers.

An example of a model run is shown in Figure 1, where the water in the disk was broken up into two species: that which originated in the inner 30 AU and that which began outside of 30 AU. Disk evolution was calculated using an $\alpha=10^{-3}$, and particle growth above 1 cm was assumed to be frustrated (that is, the largest objects formed via coagulation were 1 cm-radius particles). In the Ciesla and Cuzzi model, centimeter-sized particles would have either fallen into the category of dust, and therefore never decoupled from the gas resulting in no changes in the water distribution, or they would have been treated as *migrators* and would have drifted inward at much more rapid rates, producing much more rapid evolution than seen here. Thus the higher resolution model developed here provides a more realistic description of the dynamic evolution of water in a protoplanetary disk.

While the details change, the same general behavior as found in [4] is seen, and we are now carrying out a detailed investigation in order to understand how the timescales for this evolution depend on nebular parameters. Further, we are also quantifying the level to which "outer disk" materials are transported to the terrestrial planet region in each case. These results will be presented.

References: [1] Grossman L. et al (2008) *Rev. Min. Geochem., 68,* 93-140. [2] Lyons J. R and Young E. D. (2005) *Nature, 435,* 317-320. [3] Yurimoto H. and Kuramoto K. (2004) *Science, 305,* 1763-1766. [4] Ciesla F. J. and Cuzzi J. N. (2006) *Icarus, 181,* 178-204. [5] Cuzzi J. N. and Zahnle K. J. (2004) *ApJ, 614,* 490-496. [6] Blum, J (2010) *Res. Astron. Astroph., 10,* 1199-1214. [7] Youdin A. N. and Lithwick Y. (2007) *Icarus, 192,* 588-605. [8] Weidenschilling S. J. (1977) *MNRAS, 180,* 57-70. [9] Weidenschilling S. J. (1997) *Icarus, 127,* 290-306. [10] Estrada P. R. and Cuzzi J. N. (2008) *ApJ, 682,* 515-526. [11] Cuzzi J. N. et al. (2010) *Icarus, 208,* 518-538. [12] Chambers J. E. (2010) *Icarus, 208*, 505-517. [13] Johansen A. et al. (2007) *Nature, 448,* 1022-1025. [14] Young E. D. (2007) *EPSL, 262,* 468-483. [15] Lee J.-E. et al. (2008) *MaPS, 43,* 1351-1362.

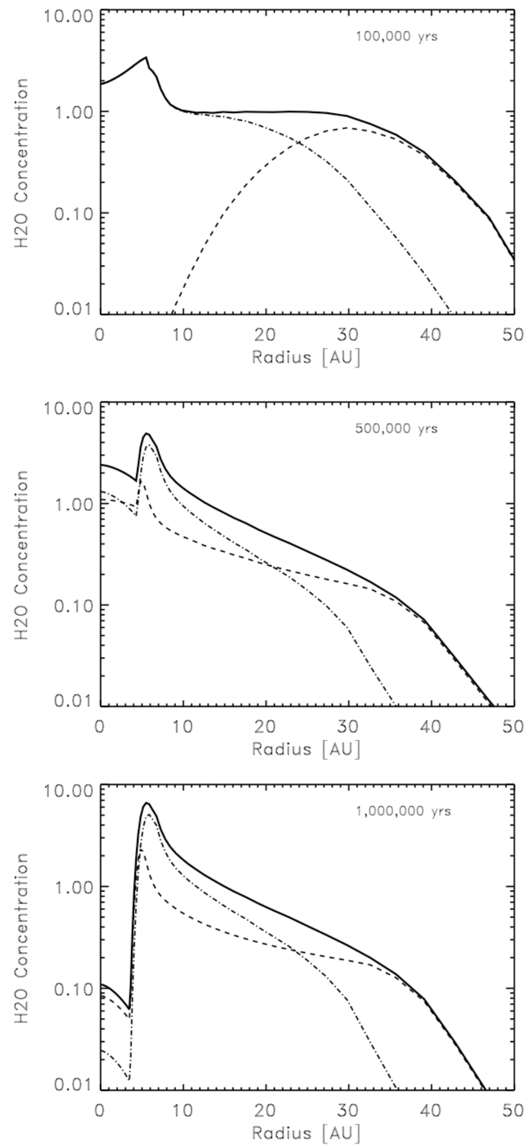

Figure 1: Temporal evolution of the water distribution in an evolving protoplanetary disk. Solid line shows the normalized concentration of all water (vapor + solids of all sizes) relative to the concentration expected for a gas of solar composition. The dot-dashed line shows the distribution of water that originated inside of 30 AU, while the dashed line represents that which originated outside of 30 AU. As can be seen dynamic processes allow for water in the outer nebula to be comparable in abundance in the terrestrial planet region as the water from the inner nebula in a time of ~500,000 years for the case presented here. The exact timing requires careful examination of water ice dynamics.