WATER TRANSPORT IN THE SOLAR NEBULA: IMPLICATIONS FOR THE MIXING OF OXYGEN ISOTOPIC RESEVOIRS. F.J. Ciesla[1], A.N. Krot[2], and J.R. Lyons[3]. [1]Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Road NW, Washington, DC 20015 (ciesla@dtm.ciw.edu). [2]Hawai'i Institute of Geophysics and Planetology, SOEST, University of Hawai'i at Manoa, Honolulu, HI 96822, USA. [3]Institute of Geophysics and Planetary Physics, UCLA, Los Angeles, CA 90095.

Introduction: The affinity of oxygen for both gaseous and solid phases makes it and its isotopes important tracers of redox conditions and isotopic reservoirs in the solar nebula. The oxygen fugacity (fO_2) recorded by chondritic meteorites ranges over several orders of magnitudes, from very high values needed to explain such minerals as ferrous olivine in ordinary and carbonaceous chondrites to very reducing conditions such as that needed to explain Si-rich metal in enstatite chondrites [1]. In addition, the chondrite classes fall into distinct regions on an oxygen three-isotope plot [2]. These observations imply that distinct chemical and isotopic environments existed in the solar nebula. Whether these environments varied with location, time, or both remains to be determined.

Ciesla and Cuzzi [3] recently demonstrated that the transport of water ice in an evolving protoplanetary disk would lead to fluctuations in the fO_2inside the snowline that varied with both time and location and argued that these fluctuations may be partly responsible for the variations in mineralogy observed in primitive chondrites. Transport of water ice may also have served as a way of enriching the inner disk with ^{16}O-poor material that was the product of CO self-shielding either in the molecular cloud from which the solar system formed [4] or in the outer nebula itself [5]. Here we apply the model of [3] to investigate how the oxygen isotopic reservoirs mix during the changes in fO_2 associated with water transport under these two different models. We also discuss the implications for the oxygen isotopic compositions of thermally processed cometary grains.

CO self-shielding models: CO self-shielding has been suggested to have operated in three different astrophysical settings to produce the oxygen isotope anomalies observed in chondritic materials (*i*-*iii*). In all three cases it is assumed that the bulk oxygen isotopic composition of the protosolar molecular cloud, as well as the average composition of the initial (thermally unprocessed) silicates, are ^{17,18}O-poor ($\delta^{17,18}O_{SMOW}$ ~ -50‰). (*i*) Clayton [6] suggested that self-shielding may have occurred near the inner edge of the solar nebula (at the X-point) where the UV photon flux was high due to the young Sun. However, Lyons and Young [7] argued that the high temperatures of this region would lead to the isotopic reequilibration of H_2O and CO, and thus erase any signatures of the self-shielding effect.

(*ii*) Yurimoto and Kuramoto [4] suggested that CO self-shielding took place in the molecular cloud from which our solar system formed. In this scenario, all water that was incorporated into the solar nebula would be enriched in heavy (^{17}O and ^{18}O) oxygen when compared to other oxygen-bearing species (CO, silicates, etc.). As icy solids grew in the solar nebula, they drifted inwards due to gas drag effects [8] where they were vaporized, resulting in the enhancement of heavy isotopes of oxygen inside the snowline.

(*iii*) Lyons and Young [5] argued that CO self-shielding took place in the very outer regions of the disk (> ~30 AU) where temperatures were cool enough to prevent the re-equilibration of CO and H_2O. In this model, water only outside of some given heliocentric distance would become enriched in ^{17}O and ^{18}O due to CO self-shielding. The icy solids that grew at these large distances drifted inwards, introducing heavy oxygen to the inner disk once they crossed the snowline.

In the case of these latter two models, the rate of oxygen isotope evolution in the inner disk will be dictated by the rate at which water ice is delivered from the outer disk. We are investigating how the rate at which the oxygen isotope ratios vary in these two models for a variety of solar nebula conditions and compare the results to the timing of the evolution inferred from chondritic materials. We are also examining how the oxygen isotope ratios vary with the changes in fO_2 of the inner protoplanetary disk.

Mixing model: We have modified the model of Ciesla and Cuzzi [3] to simultaneously track the evolution of two different solid-forming species in an evolving protoplanetary disk. The α-disk model is used to describe the evolution of the disk. Throughout the lifetime of the disk, the equations of motion for the vapor phase and the three most dynamically distinct solids – *dust* (Stokes number, *St* << 1), *migrators* (*St*~1), and *planetesimals* (*St* >> 1) – are solved to determine their distrubitions in the disk. The opacity of the disk is assumed to be proportional to the concentration of the dust species.

Results: Here we discuss the preliminary results of our modeling which shows how ^{17,18}O-poor and ^{17,18}O-rich materials mix together in the model of Lyons and Young [5]. Water is initially distributed throughout the disk at its canonical value, but is separated into two distinct isotopic reservoirs based on the starting location. Water ice produced outside 30 AU is assumed to be ^{17,18}O-rich, while water ice inside is ^{17,18}O-poor. (In the model of [5], the water inside and outside of 30 AU initially has the same isotopic compositions. Over ~10^5 yrs, water becomes enhanced in heavy oxygen due to CO self-shielding effects. Here we present a simplification of the model.) Examples of a model run are shown in Figure 1 at a snapshot of ~2 million years, where blue represents water originating outside 30 AU (^{17,18}O-rich) and green represents that water originating inside 30 AU (^{17,18}O-poor). The top panel shows how the water vapor inside the snowline is distributed between the two isotopic reservoirs. The bottom panel shows the concentration of the water throughout the disk relative to the canonical ratio, regardless of phase, and how it is distributed between the two reservoirs. The disk is assumed to have a global value of $\alpha = 10^{-4}$ and coagulation and accretion timescales $t_{coag} = t_{acc} = 10^4$ yrs. In this situation, the water in the disk undergoes the same type of evolution described in Ciesla and Cuzzi [3]: the inner disk is initially enhanced in water vapor due to the inward migration of meter-sized rubble from outside the snowline and then depleted as the inward flux of migrators decreases due to the decreased supply and increased likelihood of being accreted by planetesimals that has formed in the outer disk.

After two million years, the solar nebula is dominated by ^{17,18}O-rich water. Because this material originated at larger heliocentric distances, it was able to survive the net inward movement associated with protoplanetary disk evolution for longer periods of time. The original ^{17,18}O-poor water that remains in the disk is that which was incorporated into immobile planetesimals when the disk was younger or was able to diffuse upstream against the net flow of the disk. Mixing of the isotopic reservoirs is most rapid during the early stages of disk evolution because most of the material is in the form of mobile *dust* and *migrators*, whereas in the later stages of disk evolution immobile *planetesimals* trap material from moving within the disk.

Discussion: While only a few preliminary cases have been run, mixing of the isotopic reservoirs in these cases are all qualitatively similar to that described here. The rate and efficiency of mixing will depend on the values of α (higher values lead to more rapid mixing), t_{coag} (lower values lead to more rapid mixing), and t_{acc} (lower values inhibit mixing).

The evolution of the water distribution and the mixing of the isotopic reservoirs appear to be consistent with the chondritic record. Amoeboid olivine aggregates and most Ca,Al-rich inclusions (CAIs) are ^{16}O-rich objects that appear to have formed in environments which were near solar in fO_2. Such environments would exist during the initial stages of disk evolution prior to the influx of water ice from the outer disk, consistent with CAIs being the oldest objects in the solar system [9] and forming for a relatively short period of time [10]. Over time, the fO_2 of the inner disk rises due to the inward transport of water ice, and the nebular gas becomes progressively more ^{17,18}O-rich. This evolution can be seen in the majority of chondrules contained in the carbonaceous and ordinary chondrites, whose minerals require more oxidizing conditions than a gas of solar composition and are enriched in heavy oxygen isotopes compared to the CAIs. The peak in the enhanced fO_2 is reached after 1-2 million years, consistent with the inferred age difference between CR chondrules and CV CAIs [9]. After the peak is reached, the fO_2 of the inner disk drops to sub-solar values due to the continual removal of water vapor by advection and diffusion. This reducing environment is consistent with what is needed to form the minerals observed in the enstatite chondrites. At this point, the water vapor continues to be dominated by ^{17,18}O-rich material, allowing the enstatite chondrite chondrules to be rich in heavy oxygen isotopes as is observed.

We can also make predictions about the oxygen isotope compositions of thermally processed cometary grains. The oxygen isotope ratios evolve throughout the protoplanetary disk, also becoming progressively more ^{16}O-poor over time inside of 30 AU. Whether cometary grains were thermally processed near the Sun [11] or near where they were accreted [12], their isotopes likely mirror that of chondritic materials with the older grains being ^{17,18}O-poor and the younger grains becoming progressively ^{17,18}O-rich.

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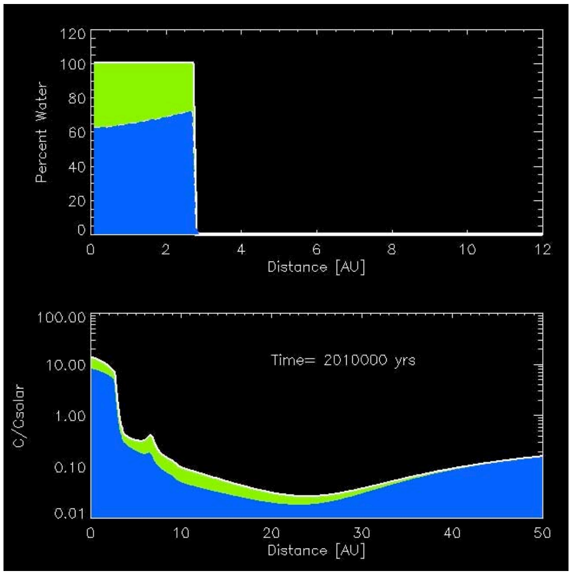

Figure 1: Snapshot after ~2 million years of evolution of the distribution of water inside the snowline (top panel) and its concentration throughout the disk (bottom panel). Green represents ^{17,18}O-poor water while blue is ^{17,18}O-rich based on the model of Lyons and Young [5].