OXYGEN ISOTOPE ANOMALIES IN THE SOLAR NEBULA INHERITED FROM THE PROTO-SOLAR CLOUD

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Introduction: Measurements of the oxygen isotopic compositions of refractory inclusions (CAIs and AOA) in meteorites indicate that they are depleted in ^{17}O and ^{18}O relative to chondrules and other terrestrial materials [1]. As all of these objects are thought to have formed in the solar nebula, this suggests that the nebula contained environments whose oxygen isotopic ratios varied with time and/or location. Theoretical studies have suggested that of CO self-shielding may have been responsible for the oxygen isotope variations in the solar nebular [2-4].

Most models of isotope selective photo-dissociation of CO consider the mass-independent oxygen isotope signatures produced either in a well-formed disk or in a collapsing proto-solar cloud separately. However, protoplanetary disks like our solar nebula are built as material from the parent molecular cloud rains down over a finite period of time. This material, which may vary in isotopic abundances from the bulk parent cloud, is then subjected to mass and angular momentum transport as it gets incorporated into the disk, some eventually being accreted by the central star, while some is pushed outwards to large distances. The dynamical evolution will impact the distribution of those isotope variations in the disk.

Here we consider the dynamical evolution of a solar nebula during and after the period when it is built from its parent molecular cloud. Specifically we apply the model of oxygen isotopic anomalies produced via self-shielding photo-dissociation of CO in the parent cloud core developed by Lee et al [5-6] to investigate how the concentrations and isotopic ratios in CO and H_2O inherited from the cloud vary with space and time in the disk as they are transported during disk evolution and the formation of the Sun.

Model Description: Our model begins with a collapsing molecular cloud in a background of external ultraviolet radiation field. The less abundant $C^{17}O$and $C^{18}O$ can be photo-dissociated deep in the cloud while the $C^{16}O$ in this region is photodissociated only in the outer layers of the cloud due to its higher abundance. The liberated O atoms bond with hydrogen to make water ice isotopologues. The details of the amount of water produced and the isotopic variations in it depend sensitively on the intensity of incident UV photons, G_0 [5-6]. Lee et al [6] performed a series of calculations for a collapsing cloud core, tracking how the density of the cloud and the abundances of CO and H_2O isotopologues vary with time. We take these results as the inputs to our dynamical model.

In simulating the evolution of a solar nebula growing within the parent cloud, we build on our previous model of material transport in a protoplanetary disk that accretes materials from its parent molecular cloud [7]. We use the standard α-viscosity model to describe the mass and angular momentum transport within the disk. We account for disk building by adopting an analytic formula that describes the addition of mass to the central star and disk as a result of infall from the molecular cloud. The rate of infall varies with time and is calculated based on the results of [6] at any given time. The physical angular momentum of the material in the star-disk system equals to its initial angular momentum in the parent cloud core. The formula describing the evolution of centrifugal radius is modified to make the inner boundary in the Lee et al. model as its up limit. Infall takes place until the mass of the molecular cloud is completely incorporated into the star-disk system.

Results: Figures 1-4 show the results of a typical model simulation. For this run we considered a 1 M⊙ molecular cloud with temperature set as 10 K. We used the proto-solar cloud model from [6] with G_0=100, which experiences a period of infall lasting 700,000 years. Material is always added to the disk inside the inner boundary of the collapse model (125 AU). We used a base value of $\alpha=10^{-3}$ throughout the disk, but augment it in regions that become gravitationally unstable.. Our model begins with a star of mass 0.05 M⊙ and no mass in the disk (beyond 0.1 AU).

Figure 1 shows how the masses of the disk and star evolve with time. The disk mass reaches its maximum value of 0.2 M⊙ at the end of infall. Subsequently, the disk mass decreases as the disk evolves and mass is accreted onto the star as part of its final pre-main sequence growth. Figure 2 shows how this mass is distributed as it plots the surface density of the disk at different times during its evolution.

Figures 3 and 4 show how the abundances of water ice and CO within the infalling material vary with time and the oxygen isotopic composition evolution of each species based on the fits of Lee et al. model [6].

Figure 5 shows how the $\delta^{18}O$ of H_2O varies with location in the disk with time. During the earliest evolution, there are strong variations of the isotopic composition of water in both time and location. This is due to the changing isotopic compositions of materials being added to the disk with time. Once infall ceases, disk evolution begins to smooth out gradients, leading to a more homogenized disk.

Discussion: While the isotopic variations in H_2O reported here have large positive values early, which differ from the values found in CAIs, we stress that we are only presenting the results for a single model run. Different results are expected for other choices of G_0 as well as dynamical parameters that we continue to explore. Further, we must consider when CAIs formed, and the compositions of all materials in the CAI factory. Nonetheless, we expect that isotopic variations in the protosolar cloud would have produced heterogeneities in the early solar nebula as the composition of the infalling material changed with time. Once infall ceased, dynamic processes in the disk would work to smooth out such variations.

Once incorporated into the disk, other processes may operate to combat the isotopic homogenization we find here. For example, as water ice is incorporated into solids which begin to decouple from the gas, they will carry water inwards with time, reshaping the overall distribution of water in the protoplanetary disk [8,9]. Understanding how this transport affects the isotopic variations in the water requires understanding these dynamics in detail, which requires higher resolution studies of water ice dynamics as being investigated by [10].

References: [1] Yurimoto, H. et al. (2008) *Reviews in Mineralogy and Geochemistry*, vol. 68, 141-186. [2] Clayton, R.N. (2002) *Nature*, 415, 860–861.[3] Yurimoto, H. and Kuramoto, K. (2004) *Science* 305, 1763–1766. [4] Lyons, J.R. and Young, E.D. (2005) *Nature*, 435, 317–320. [5] Lee, J.-E. et al. (2004) *ApJ*, vol. 617, 360-383. [6] Lee, J.-E. et al. (2008) *Meteoritics & Planetary Science*, vol. 43, 1351-1362. [7] Yang, L. and Ciesla, F. J. (2010) *LPS XLI,* #1461. [8] Cuzzi, J. N. and Zahnle K. J. (2004) *ApJ, 614,* 490-496. [9] Ciesla, F. J. and Cuzzi, J. N. (2006) *Icarus, 181*, 178-204. [10] Ciesla, F. J. (2011) *This Meeting.*

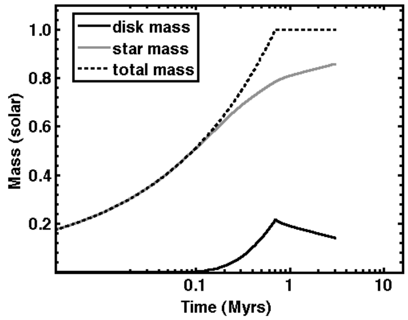

Figure 1: The mass evolution of the disk and star.

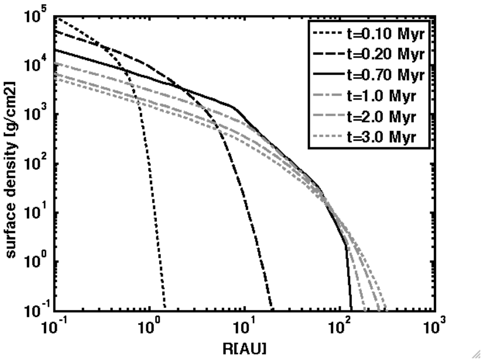

Figure 2: The gas surface density evolution of the disk.

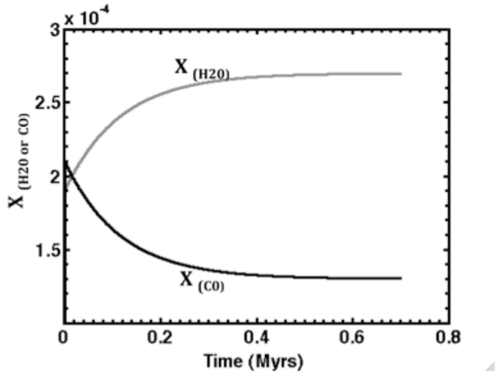

Figure 3: The concentrations of H_2O and CO in infalling mass.

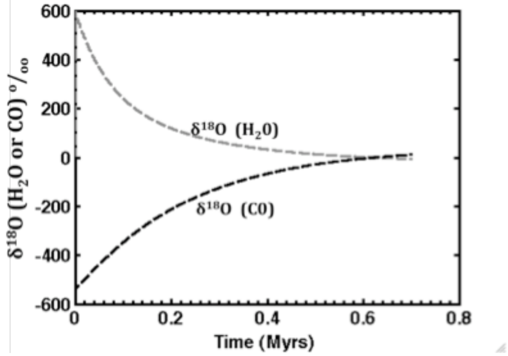

Figure 4: the $\delta^{18}O$ evolution of the infalling H_2O and CO

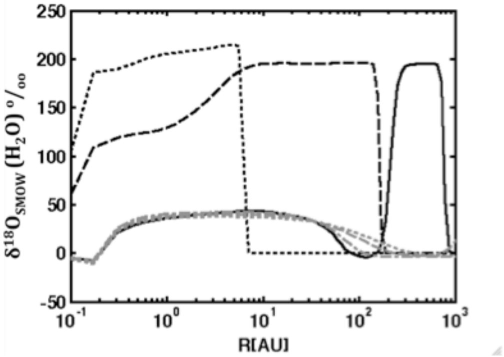

Figure 5: the $\delta^{18}O(H_2O)$ distributions in the disk at different times. The lines are at the same times as those in Figure 2.