

THE TIMING OF OXYGEN ISOTOPE VARIATIONS IN THE EARLY SOLAR SYSTEM: A MEASURE OF RADIAL TRANSPORT IN THE SOLAR PROTOPLANETARY DISK? E. D. Young¹, ¹Department of Earth and Space Sciences and Institute of Geophysics and Planetary Physics, University of California Los Angeles, 595 Charles Young Drive East, 2676 Geology Building, Los Angeles, CA 90095 (Email: eyoung@ess.ucla.edu).

Introduction: When considered in the context of realistic models for disk chemistry and transport, the oxygen isotopic compositions of meteoritical materials may serve as indicators of timescales of large-scale processes in the solar circumstellar disk. Optically thin surfaces of the disk were likely sites for generating ^{16}O isotope variability in the early Solar System. Astrochemical reaction network calculations predict that a robust feature of these photoactive horizons of the disk was conversion of CO gas to ^{16}O -poor (high $\Delta^{17}\text{O}$) H_2O ice on a timescale of 10^5 years [1]. Because far ultraviolet (FUV) fluxes were so great within 5 AU of the nascent Sun, the CO self shielding oxygen isotopic effect was an outer disk phenomenon [2] transferred to the inner disk. Calculations depicting transport in the disk suggest that CO photodissociation at disk surfaces triggered a wave of high- $\Delta^{17}\text{O}$ H_2O that passed from surface regions through the outer disk and into the rocky planet-forming region on a timescale of 10^5 to 10^6 years. The scenario deduced from such models can be compared with the meteoritical evidence for the timing of changes in $\Delta^{17}\text{O}$ in differentiated meteorites, calcium aluminum-rich inclusions (CAIs), chondrules, and chondrite matrix.

CO Self Shielding: Within a few AU of the central star FUV fluxes were too great to permit trapping of the oxygen isotopic effects of CO photodissociation in H_2O , or in any other oxygen-bearing molecule, unless CO was added from outside the disk at unrealistically high rates. Trapping of the CO self shielding isotopic effect must therefore have been an outer disk phenomenon, necessitating inward transport of the ^{16}O -poor, high- $\Delta^{17}\text{O}$ signal into the region of terrestrial planet formation in the inner disk (Fig. 1). Simple box models that incorporate timescales of transport within accretion disks can be used to predict the timescale of transfer of high- $\Delta^{17}\text{O}$ H_2O produced by CO photochemistry in the outer disk to the inner disk. Inward radial transfer of high- $\Delta^{17}\text{O}$ water would have taken place either continuously during the infall phase of disk evolution or by virtue of a wave of high- $\Delta^{17}\text{O}$ H_2O that passed from disk surfaces through the outer disk and into the rocky planet-forming region on a timescale of 10^5 to 10^6 years post infall (Fig. 2).

Many observations are consistent with photodissociation of CO in the diffuse regions of the solar nebula as an explanation for the slope-1 line in oxygen three-isotope space. It accounts for the fact

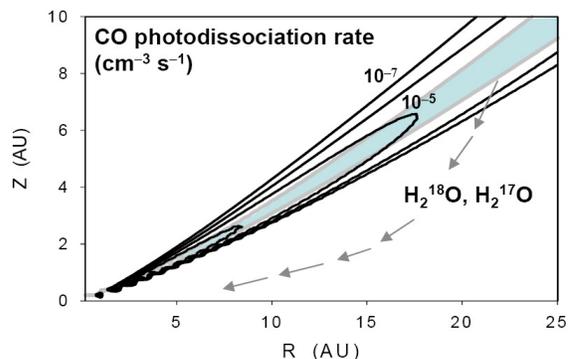


Fig. 1 Disk model showing contours of CO dissociation rate and the region between optical depth $\tau = 1$ and 4 for CO (grey) where self shielding by CO obtains. Arrows show transport of high- $\Delta^{17}\text{O}$ H_2O required by such a model.

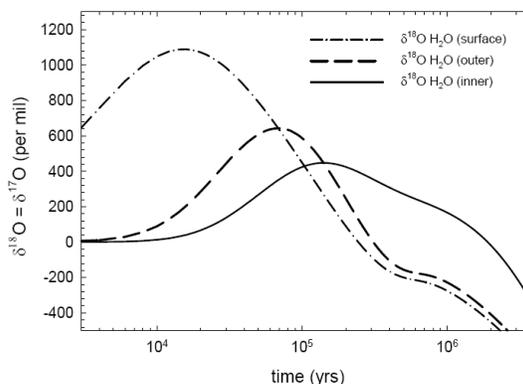


Fig. 2 Result of box model calculation for the oxygen isotopic evolution of H_2O in surficial, outer, and inner regions of the solar circumstellar disk. The result shows the timescale required to transport a high- $\Delta^{17}\text{O}$ signal as water into the region of terrestrial planet formation.

isotope space. It accounts for the fact that H_2O was almost certainly depleted in ^{16}O (enriched in ^{18}O and ^{17}O , i.e., enriched in H_2Q) relative to silicates and other metal oxides in the Solar System [1, 3, 4]. Production in the outer solar nebula also provides a natural explanation for the correlation between ^{16}O and the refractory nature of solids; many refractory minerals

such as those found in CAIs should have retained their original ^{16}O -rich compositions because they would have had limited opportunity for reaction with H_2O during transit through the nebula despite numerous heating events. Less refractory materials like Fe-bearing olivine and glass that comprise chondrite matrix, materials that are generally ^{16}O poor, had greater opportunity for exchange.

Solid-state exchange of oxygen isotopes and H_2O gas: The assertion that exchange with H_2O is consistent with the oxygen isotope data for meteorites can be examined quantitatively with reference to self diffusion coefficients for oxygen in various pertinent mineral phases that comprised dust, chondrules, and CAIs in the early Solar System. The overall picture deduced from diffusivities of oxygen is one in which Fe-bearing dust and chondrules made from that dust acquired their oxygen isotope ratios by exchange with H_2O while important constituents of igneous CAIs could not exchange. If $\Delta^{17}\text{O}$ of exchangeable gas in the inner solar system rose with time (Fig. 2), $\Delta^{17}\text{O}$ in various minerals provides a record of processing in the disk.

Self diffusion coefficients for Fe-bearing olivine, representing the less refractory dust in the solar nebula, and spinel, pyroxene and melilite, representing the more refractory CAIs, are known [5, 6]. These diffusivities are compared by converting them into maximum radii of mineral grains that will experience complete oxygen isotope exchange for a given temperature and time. These maximum radii r_{max} are given by the expression

$$r_{\text{max}} = \pi \left(\frac{-t(D_0 \exp(-E_a/(kT)))}{\ln(C/C_s)} \right)^{1/2}$$

where D_0 is the preexponential for the diffusion coefficient, E_a is the activation energy for the diffusion coefficient, t is the duration for diffusion, and C/C_s is the ratio of concentration to the concentration imposed externally on the surface of the grain. Integrated heating times are thought to have been on the order of 10^2 to 10^3 years in the nebula [7-9]. For $t = 500$ years, $C/C_s = 0.1$, and $T = 1600$ K (a subsolidus temperature for both CAIs and olivine at nebular pressures) r_{max} values are $0.3 \mu\text{m}$ for olivine at appropriate fugacities of O_2 , $22 \mu\text{m}$ for spinel, $3607 \mu\text{m}$ for melilite, and $130 \mu\text{m}$ for pyroxene. The r_{max} values can be compared with typical grain sizes of $\ll 1 \mu\text{m}$ for olivine in matrix, ~ 30 to $50 \mu\text{m}$ for spinel in igneous CAIs, $\geq 1000 \mu\text{m}$ or larger for melilite in igneous CAIs, and $\geq 500 \mu\text{m}$ for pyroxene in igneous CAIs. The comparison

suggests that fine-grained sub-micron sized dust comprising matrix and precursors to CAIs both could have equilibrated with H_2O given the opportunity. Matrix dust is ^{16}O poor, allowing for the interpretation that dust comprising matrix was indeed heated in the inner disk during passage of the ^{16}O -poor H_2O wave. CAIs, however, are generally ^{16}O rich and yet must have spent some time in the inner solar nebula where temperatures were high, suggesting that dust precursors to CAIs avoided being heated in the presence of ^{16}O -poor H_2O . This interpretation is consistent with early formation of CAIs prior to passage of the H_2O wave in the inner nebula (i.e., at $t \leq 10^5$ years). In the case of igneous CAIs crystallized from melts and subsequently heated, the r_{max} values predict that spinel and pyroxene in these CAIs should have retained their ^{16}O -rich compositions while melilite would not. Spinel will not have entered the melt during partial melting events because it is the liquidus phase (the last solid phase to remain on the liquidus with heating), further insulating it from exchange [10]. As a consequence, one would predict that spinels should have remained ^{16}O rich even after numerous partial melting events and indeed spinels in igneous CAIs are generally ^{16}O rich. Pyroxenes in CAIs will have melted near the CAI eutectic and preservation of ^{16}O -rich compositions in many, but not all, pyroxenes could imply some melting prior to (or after) the passage of the ^{16}O -poor wave of H_2O in the inner nebula.

These predictions are consistent with observations [6]; igneous CAI spinel and pyroxene tend to be ^{16}O rich while igneous CAI melilite and the matrix of the meteorites are generally ^{16}O poor. The ^{16}O -poor compositions of chondrules are also consistent with this scenario because dust similar to matrix was likely the precursor to chondrules. Melting of chondrules would have facilitated their exchange with H_2O gas due to the rapid self diffusion of O in silicate melt.

References: [1] Lyons J. R. and Young E. D. (2005) *Nature* 435, 317-320. [2] Young E. D. (2007) *Earth and Planetary Science Letters* (in press). [3] Sakamoto N. *et al.* (2007) *Science* 317, 231-233. [4] Yurimoto H. and Kuramoto K. (2004) *Science* 305, 1763-1766. [5] Ryerson F. J. *et al.* (1989) *Journal of Geophysical Research* 94, 4105-4118. [6] Ryerson F. J. and McKeegan K. D. (1994) *Geochimica et Cosmochimica Acta* 58, 3713-3734. [7] Shaha A. and Young E. D. (2007) *Earth and Planetary Science Letters* 257, 497-510. [8] Simon J. I. *et al.* (2005) *Earth and Planetary Science Letters* 238, 272-283. [9] Young E. D. *et al.* (2005) *Science* 308, 223-227. [10] Stolper E. M. and Paque J. M. (1986) *Geochimica et Cosmochimica Acta* 50, 1785-1806.