GIANT PLANET FORMATION AND THE EVOLUTION OF OXYGEN ISOTOPES IN THE SOLAR SYSTEM.

L. P. Keller[1], C. Snead[2], and K. D. McKeegan[2], [1]ARES, Code XI3, NASA/JSC, Houston, TX 77058 (Lindsay.P.Keller@nasa.gov). [2]Dept. of Earth, Planetary, and Space Sciences, UCLA, Los Angeles, CA 90095.

Introduction: The oxygen isotopic compositions of the vast majority of meteoritic materials plot along a slope ~1 line in a three isotope diagram. The distribution of compositions is widely believed to reflect mixing between two major reservoirs, one that is ^{16}O-rich and the other that is ^{16}O-poor. The nature of the ^{16}O-rich reservoir is well constrained by measurements of implanted solar wind oxygen returned by the Genesis mission [1] and anchors the three-isotope diagram at δ^{18}O, δ^{17}O ~(-60‰,-60‰, "solar"). The ^{16}O-poor reservoir however, is controversial and poorly understood. Canonical self-shielding models predict the development of ^{16}O-poor water-rich reservoir from gas that was initially ^{16}O-rich. Evidence for this ^{16}O-poor reservoir is sparse in the meteoritic record, but several examples do exist in primitive chondritic meteorites, as well as regions within interplanetary dust particles [e.g. 2-6]. Overall however, the compositions of most meteoritic materials plot between solar and (δ^{18}O, δ^{17}O; 0‰,0‰, "planetary").

An intriguing aspect of the three isotope diagram is the concentration of compositions around and generally below the intersection of the slope 1 line and the slope ½ terrestrial fractionation line (TFL). Another attempt at explaining this distribution assumes that the presolar dust was relatively ^{16}O-poor with a planetary composition, while the primordial gas was ^{16}O-rich [7] and that the distribution of O isotopic compositions for refractory meteoritic materials reflect mixing between these 2 reservoirs. However, this model does not account for the remarkably ^{16}O-poor solids that are known to exist [3]. Here, a model for the distribution of O isotope compositions in meteoritic materials is proposed, based on the self-shielding model [8] but allowing for disk processes (primarily giant planet formation) to control the mixing between reservoirs.

Results and Discussion: The initial assumption here is that the pre-molecular cloud dust and gas shared the same ^{16}O-rich composition, given that grain processing in the interstellar medium is believed to have resulted in efficient chemical and isotopic homogenization [9]. Thermal processing of this dust likely began during the collapse phase of the protosolar core and continued through the time the Sun was a Class I-III protostar until the transition to a debris disk. Refractory inclusions are among the earliest formed solids and are ^{16}O-rich, with the majority forming within ~0.2 My after T_0 (defined as 4567.3 My [10]). The major epoch of chondrule formation was largely complete by ~4 My, with the majority of chondrules forming ~2-3 My after T_0 [10] and have δ^{18}O, δ^{17}O clustering close to planetary (Δ^{17}O of ~-5 to 0 ‰, [11]). Krot *et al.* [7] have suggested that this distribution reflects mixing between "primordial" ^{16}O-poor dust and ^{16}O-rich gas, whereas we interpret the trend as an exchange between ^{16}O-rich inner solar system materials with a heavy ^{16}O-poor reservoir that was situated in the outer solar system [e.g. 12]. Furthermore, we propose that this mixing was disrupted by the formation of a gas giant planet.

Inward movement of material from the outer protoplanetary disk occurs through mass transfer along the midplane as the proto-Sun was actively accreting disk material. Preservation of angular momentum results in disk winds and bipolar outflows that distributed refractory (anhydrous) and relatively reduced (Fe metal-bearing) materials that formed close to the proto-Sun to the outer reaches of the disk [13-16]. Inner solar system bodies are water-poor, while the outer solar system bodies are water-rich, suggesting that the water-condensation line in the disk (i.e. the snowline) separated these two distinct regions of the protoplanetary disk [14].

While stellar accretion was active, ^{16}O-poor ices were brought into the inner solar system and interacted with ^{16}O-rich materials producing intermediate O isotopic compositions along the slope 1 trend observed in the 3 isotope plot [12, 17]. However, the mixing between these two reservoirs effectively stopped at some point, and inner solar system bodies accreted (the terrestrial planets and main belt asteroids) within ~5 My of T_0 [18]. A possible mechanism for the disruption of the mixing between the ^{16}O-poor outer solar system volatile reservoir and inner solar system refractory materials was the formation of a gas giant planet (e.g. Jupiter). Once proto-Jupiter grew to a sufficient size (~20 Earth masses, [14]), it opened a gap in the protoplanetary disk. The presence of this gap and its effects on particle movement in the disk prevented any further substantial transfer of outer solar system ices and silicates into the inner solar system [14].

In this model, if Jupiter had not formed and opened a gap, the inner solar system would be more water-rich than at present, and the O isotopic compositions of solids would have continued to evolve beyond planetary up the slope 1 line. Dust models suggest that some fine-grained (<150 μm) particles can transit the gap as long as they are strongly coupled to the gas [19,20], however, these tiny particles are inefficiently captured by planetesimals and are rapidly swept up by the proto-Sun. Modeling efforts [14] have constrained the time when Jupiter achieved sufficient mass to open a gap in the disk to ~3 My after T_0, and that is consistent the the ages of the youngest (dated) nebular solids (chondrules).

Consequences: Primitive materials from water-rich bodies that interacted with a ^{16}O-poor reservoir either through oxidation or hydration should show evidence of mixing along the slope 1 line beyond (above) the TFL. Indeed, several examples exist including cosmic symplectites (COS) and matrix analyses from Acfer 094 [3,21], the magnetite compositions reported from unequilibrated ordinary chondrites [2] and from interplanetary dust particles, cosmic spherules, and Stardust samples [4-6, 22-26]. Most of these materials likely reflect outer solar system grains that successfully transited the gap opened by Jupiter. The oxygen isotopic compositions of these materials are direct evidence for the existence of a heavy, ^{16}O-poor reservoir in the outer solar system that likely resulted from self-shielding.

The apparent lack of ^{16}O-rich primordial dust in meteoritic materials has been taken as evidence against self-shielding models [7]. Primitive bodies from the outer solar system should be the best repositiories of the primordial (presolar) dust building blocks. However, the vast majority of O isotopic measurements are confined to inner solar system materials that have undergone thermal and/or aqueous processing that effectively works to erase the primordial dust signature. Order of magnitude variations in presolar grain abundances (one measure of "primitiveness") among cometary IDPs suggest that even cometary solids experienced significant variations in the degree of processing in the solar nebula [27]. Cometary solids that have been analyzed in the laboratory are dominated by anhydrous materials with inner solar system origins, many of which formed at high temperatures [e.g. 28-31]. Furthermore, the limited Al-Mg isotopic measurements that exist for bonafide comet dust lack evidence for live ^{26}Al, thus suggesting late addition of these materials to the comet forming region [e.g. 32, 33].

Astronomical observations of contemporary interstellar dust suggest that the primordial (presolar) dust building blocks were dominantly amorphous fine-grained silicate particles [34]. The chemical composition of this primordial dust was solar for rock-forming elements, by definition, but the heterogeneity about this average composition is unknown. This primordial dust has not yet been directly measured isotopically because no viable candidates for this dust (amorphous silicate dust with ***solar*** chemical composition) have been identified to date in meteoritic materials [30]. Examples of this dust may have been present in comet 81P/Wild 2 samples returned by Stardust, but were altered or destroyed by the capture process [35].

The extent to which fine-grained primordial building blocks are preserved in comets is still an open question that could be resolved with a comet nucleus sample return mission. Similarly, while outer solar system volatiles are predicted to be ^{16}O-poor [12], current astronomical isotopic measurements of comets and icy satellites lack the necessary precision to make this determination. This is another knowledge gap that could be addressed with a comet nucleus sample return and/or in situ analyses of cometary ices with instruments having the requisite precision.

Conclusions: We propose a model whereby the formation of proto-Jupiter opened a gap in the protoplanetary disk that prevented further mixing between ^{16}O-rich dust and a ^{16}O-poor ices. The lack of further mixing resulted in the concentration of O isotopic compositions of most inner solar system materials around planetary. The presence of meteoritic materials with Δ^{17}O >5 (in some cases much greater) requires a heavy O reservoir in the outer solar system that developed via self-shielding.

References: [1] McKeegan, K. D. *et al.* (2011) *Science*, 332, 1528. [2] Choi, B-G. *et al.* (1998) *Nature*, 392, 577. [3] Sakamoto, N. *et al.* (2007) *Science*, 317, 231. [4] Starkey, N. A. *et al.* (2014) *GCA*, 142, 115. [5] Snead, C. J. *et al*. (2016) *LPSC* 47, #2850. [6] McKeegan, K. D. (1987) PhD Thesis, Wash. Univ. [7] Krot, A. N. *et al.* (2010) *ApJ*, 713, 1159. [8] Clayton, R. N. (2002) *Nature*, 415, 860. [9] Zhukovska S. *et al.* (2008) *AA*, 479, 453. [10] Connelly, J. N. *et al*. (2012) *Science*, 338, 651. [11] Kita, N. *et al.* (2016) *MAPS*, #6378. [12] Young, E. D. (2007) *EPSL*, 262, 468. [13] Ciesla, F. J. (2007) *Science*, 318, 613. [14] Morbidelli, A. *et al*. (2015) *Icarus* 267, 368. [15] Brownlee, D. E. *et al*. (2006) *Science*, 314, 1711. [16] Shang, Z. *et al*. (2000) *Space Sci Rev* 92, 153. [17] Ciesla, F. & Cuzzi, J. (2006) *Icarus* 181, 178. [18] Johansen, A. *et al*. (2015) *Sci. Adv*. 1:e1500109. [19] Paardekooper, S-J & Mellema, G. (2006) *AA* 453, 1159. [20] Zhu, Z. *et al* (2012) *ApJ* 755, 6. [21] Nittler, L. *et al.* (2015) *LPSC* 46, #2097. [22] Yada, T. *et al.* (2005) *GCA* 69, 5789. [23] Rudraswami, N. G. *et al*. (2016) *GCA* 194, 1. [24] Keller, L. P. *et al.* (2016) *MAPS*, #2525. [25] Snead, C. J. & McKeegan, K. D. (2015) *MAPS*, #5253. [26] Snead, C. *et al*. (2017) this volume. [27] Messenger, S. *et al*. (2016) Goldschmidt. [28] Brownlee, D. E. (2014) *AREPS* 42, 197. [29] Keller, L. & Messenger, S. (2005) *ASP Conf, Series*, 341, 657. [30] Keller, L. P. & Messenger, S. (2011) *GCA*, 75, 5336. [31] McKeegan, K. D. *et al.* (2006) *Science* 314, 1724. [32] Matzel, J. *et al.* (2010) *Science* 328, 423. [33] Nakashima, D. *et al*. (2015) *EPSL* 410, 54. [34] Kemper, F. *et al*. (2004) *ApJ*, 609, 826. [35] Leroux, H. (2012) *MPS* 47, 613.