

THE OXYGEN ISOTOPE COMPOSITION OF THE SUN AND IMPLICATIONS FOR OXYGEN PROCESSING IN MOLECULAR CLOUDS, STAR-FORMING REGIONS, AND THE SOLAR NEBULA.

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Introduction: Oxygen isotope compositions of solar system materials show wide variability and therefore potentially offer insights to the evolution of a molecular cloud through accretionary disk to planetary system. The discovery of large ^{16}O excesses in refractory inclusions was originally ascribed to a late-stage nucleosynthetic input where short-lived ^{26}Al and ^{50}Ti were brought in close to the formation of the solar system [1]. However, non-linear isotope fractionation was discovered in our own atmosphere leading to an attempt to model the ^{16}O anomaly in refractory inclusions as the result of high temperature processing in the solar nebula [2,3]. More recently, the oxygen isotope variability has been ascribed to photochemical processing of CO in the solar system [4] or inheritance from the molecular cloud where photochemical reactions cause variations in ^{16}O abundance between gaseous and solid phases, and thermal processing in the solar system fractionates these reservoirs [5].

The key ingredient to any model explaining the oxygen isotope systematics of the solar system is the composition of the Sun. Predictions for the solar oxygen isotope composition generally fall into either end of the ^{16}O fractionation line characterizing solar system compositions, viz. either the Sun has a composition close to terrestrial [1,2], or enriched in ^{16}O [3-5].

Oxygen in the Sun: We have proposed that the oxygen isotope composition of the Sun is recorded in lunar metal grains that have been exposed to the solar wind [6]. The oxygen isotope composition preserved below the surface of these grains is depleted in ^{16}O by $54 \pm 5 \text{ ‰}$ ($2\sigma_m$); that is, relative to the terrestrial oxygen isotope composition, it represents a complementary depletion in ^{16}O to the ^{16}O enrichment in refractory inclusions (Fig. 1). While a terrestrial (and/or lunar) oxygen isotope composition is preserved at the grain surface, there is no indication of oxygen with ^{16}O enrichment in these grains.

Modelling Oxygen Systematics: The most likely mechanism for ^{16}O fractionation is UV predissociation of CO and self-shielding. Clayton [4] has proposed this mechanism was operating in the early solar system whereby the nebula CO is irradiated by solar UV leading to self-shielding and elevated ^{17}O and ^{18}O within the disk. However, the

self-shielding mechanism is only observed in the cold molecular cloud environment, and so Yurimoto and Kuramoto [5] have proposed that the solar system oxygen systematics are inherited from the molecular cloud precursor to the solar system. The ^{16}O -enriched mixing line between refractory inclusions and compositions of planetary bodies is interpreted as reflecting a mixture between refractory solids from the molecular cloud, and altered materials that have reacted with ^{17}O , ^{18}O released from CO predissociation. Both the Clayton [4] and Yurimoto and Kuramoto [5] models predict that the solar oxygen isotope composition should be enriched in ^{16}O , and close to the composition of refractory inclusions, because photochemical processing can only lead to ^{16}O enrichment in the CO gas and the solids are always enriched in ^{17}O , ^{18}O .

Our inference that the Sun is depleted in ^{16}O , relative to terrestrial, is therefore at odds with the photochemical predissociation type of model. However, one of the assumptions of the Yurimoto and Kuramoto model is that the various reservoirs (^{16}O -enriched CO, refractory solids, ^{17}O , ^{18}O -enriched altered solids; Fig. 2), are preserved during disk accretion. It is not evident that this should be the case with gas-solid fractionation commonly taking place in star-forming regions. If the gas-solid ratio is changed during the formation of the accretion disk of the solar system, then the composition of the disk may differ from that of the molecular cloud. Specifically, removal, or partial removal of the complementary ^{16}O enriched CO reservoir will move the nebula to a heavier, i.e. more ^{16}O -depleted composition, relative to the average starting composition. Removal of the C^{16}O -enriched reservoir need not require depletion of gas relative to solid, rather mixing of the unfractionated CO from the outer nebula will also change the CO reservoir composition. The composition of the bulk average will therefore reflect a mixture of components that are not necessarily genetically related. Only in the case of a closed system will the Sun have the same composition as the refractory solids.

If this is the case, the oxygen isotopic composition of the Sun indicates substantial gas-solid fractionation in the star-forming region of our solar system. The relationship between the oxygen isotope compositions of the Sun, refractory dust, and the

^{17}O , ^{18}O -altered dust contributing to the accretionary disk are not related to solar system formation but set in the molecular cloud [5] and in the building of the accretion disk. Thermal processing within the solar nebula simply unmixes these components so that the highest temperature objects (refractory inclusions, chondrules) reveal the original composition of the molecular cloud (refractory solids of [5]; see Fig. 2). As such, there is no mechanism required for ^{16}O exchange between gas and solid phases in the solar nebula.

Similarly, the oxygen isotopic composition of the Sun does not support a causal mechanism via photochemistry for non-linear isotope fractionation in the early solar system. Rather, the oxygen isotopic composition of the Sun is a further manifestation of molecular cloud processing, in accord with the model of Yurimoto and Kuramoto [5], and gas-solid fractionation and mixing in the star-forming region.

References: [1] Clayton R. N. et al. (1973) *Science*, **182**, 485. [2] Thiemens M. (1999) *Science*, **283**, 341; [3] Nuth J. et al. (1998) *Earth, Moon & Planets*, **80**, 73; [4] Clayton R. N. (2002) *Nature*, **415**, 860; [5] Yurimoto H. and Kuramoto K. (2004) *Science*, **305**, 1763; [6] Ireland T. R. et al. (2004) *Lunar Planet. Sci.* **XXXV**, Abstract #1448; [7] Epstein S. and Taylor H.P.J. (1971) *Proceedings of the Second Lunar Science Conference* **2**, 1421-1441.

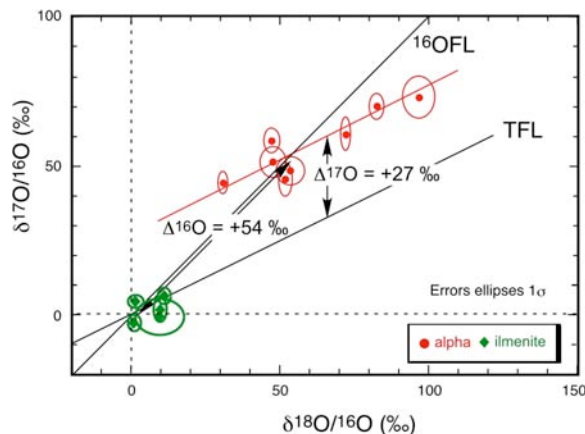


Figure 1. Oxygen isotopic composition in lunar metal grains from lunar soil 10084 attributed to solar wind implantation. Shown are analyses from grain alpha (red circles) that exclude surface contribution of isotopically near lunar or terrestrial composition. The analyses of grain alpha lie on a mass fractionation line that is offset from the terrestrial

mass fractionation line (TFL) by +27 ‰. The variable mass fractionation is probably a combination of instrumental and intrinsic mass fractionation. The clustering of points close to the ^{16}O -fractionation line (^{16}OFL) suggests the original composition is due to a ^{16}O depleted source, that is the Sun has an oxygen isotope composition depleted in ^{16}O by 54 ± 5 ‰ ($2\sigma_m$). Shown for comparison are oxygen isotope compositions of lunar ilmenite grains analysed during the same analytical period whose bulk composition has $\delta^{18}\text{O}$ of ca. +3.9 ‰ [7].

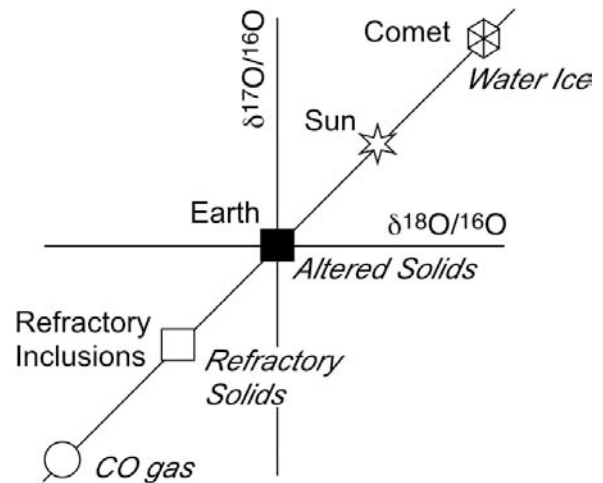


Figure 2. Schematic diagram of oxygen reservoirs in the solar system (non-italics) and corresponding sources in the molecular cloud (italics) according to [5]. The original bulk composition of the molecular cloud is represented by *Refractory Solids*. Predissociation yields a C^{16}O -enriched *CO Gas* and ^{17}O , ^{18}O radicals that quickly form *Water (ice)*. Reaction of water with refractory solids yields *Altered Solids*. In the solar system, the Earth is composed predominantly of these altered solids, refractory inclusions probably reflect the refractory solids; cometary water may represent water ice from the molecular cloud. Mixing of the altered solids and refractory solids yields the CAI mixing line. The measurements in Fig. 1 suggest that the Sun is depleted in ^{16}O relative to even the altered solids. This can only happen in the predissociation-type models if the CO -gas reservoir is not closed (removal, or mixing with normal CO) and the average can move towards heavier compositions. Such gas exchange most likely occurs in the star-forming region.