THE ^{26}Al – OXYGEN ISOTOPE CONUNDRUM.

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This note proposes a possible solution to the conundrum presented by the observed wide range of ^{26}Al/^{27}Al with a very restricted range in ^{18}O/^{16}O and ^{17}O/^{16}O in very refractory minerals (e.g., corundum, hibonite) and inclusions (e.g., corundum-, hibonite-, and grossite-rich). It follows on a study of the Egg-3 CAI where it was demonstrated that there are CAIs with the canonical ^{26}Al/^{27}Al ratio of $\sim 5.25\times10^{-5}$ but with different initial ^{26}Mg/^{24}Mg ratios [1]. These workers discussed the problem of ^{26}Al, solar oxygen and the infall problem. The oxygen-isotope compositions for primary minerals in most CAIs are ~ −50‰ for both ^{17}O/^{16}O and ^{18}O/^{16}O ratios relative to the standard mean ocean water [e.g., 2]. These compositions are similar to oxygen-isotope composition of the solar wind returned by the GENESIS spacecraft and considered to represent the Solar value [3]. The inferred initial ^{26}Al/^{27}Al ratios in the ^{16}O-rich CAIs and refractory minerals range from $\sim 5\times10^{-5}$ down to $\sim 10^{-6}$ [e.g., 2, 4]. Insofar as these materials represent processes in the solar nebula and the protosolar molecular cloud, it has been most difficult to reconcile the results with a nebula that was isotopically "homogeneous" on a large scale at some initial time. This has led to a host of models that propose late injection of ^{26}Al from a neighboring stellar source (supernova, asymptotic giant branch star, Wolf-Rayet star, stellar wind) and assignment of ^{26}Al-poor/free refractory grains and inclusions as "the first condensates" in the early solar nebula [e.g., 5].

The solar nebula has long been known to be isotopically heterogeneous from reliable and precise measurements of a large number of elements (e.g., Mg, Ba, Sr, Fe, Ni, Sm, Nd, Ne, Xe, Cr, Ti, Mo, Ru, W, Os, Pt, and O) (see [1] and references therein). With the exception of O, most elements have only small (< 0.1‰) isotopic shifts relative to terrestrial standards. These isotopic "anomalies" reflect small differences in the proportions of nucleosynthetic components that make up the average solar mix. The range in oxygen isotopic shifts is ~5% which is orders of magnitude greater than found for almost all other elements. The oxygen isotopic "anomalies" are not correlated with any nucleosynthetic effects in other elements. The discovery of the mass-independent oxygen-isotope effects [6] has been a focus of intense study and speculation. This important discovery appeared to require the coexistence of two oxygen-isotope reservoirs in the solar nebula, ^{16}O-rich and ^{16}O-poor, which on a three-isotope diagram plot along slope-1 line. The origin of these reservoirs remains unsolved. The original proposal that the ^{16}O enhancement was due to injection of supernova material is not substantiated due to the absence of correlated nuclear effects and the magnitude of the ^{16}O shift. The discovery of "non-mass dependent" isotopic effects in ozone by [7] and the observations by [8] on isotopically anomalous ozone in the stratosphere as well as extensive laboratory experiments has clearly demonstrated that such effects are widespread and common. Theoretical study by [9] has shown the explanation for the case of ozone, but no theory has explained the oxygen results found in condensed phases in bulk meteorites and rocks. The most popular and plausible proposal is that of self-shielding by C^{16}O in the gas phase resulting in an environment with low ^{16}O but the same ^{18}O/^{17}O [10–13]. There is thus a chemical-physical process that is considered to have taken place in the protoplanetary disk. It took place at a later time than the formation of CAIs as demonstrated by the O-isotope studies of chondrules and asteroids and their chronologies. This ^{16}O deficient oxygen was produced and altered condensed phases by some unknown exchange process. It is this material which makes up the Earth, Mars and the Asteroidal belt. It is effectively the value associated with the terrestrial planets with small mass dependent fractionation effects superposed.

The refractory minerals and CAIs are the result of a process that involves heating of material containing oxides and silicates to very high temperatures (~2500 K) followed by evaporation and condensation. The produced phases (particularly Al_2O_3) are very resistant to chemical alteration. This process can, of course, be produced in the laboratory today and does not define a time or a single event.

The oxygen isotopic composition at the level of precision required has not been determined for the Sun. The experiments investigating the O isotopes from the solar wind from the GENESIS mission [3] clearly point to the Sun having higher ^{16}O relative to the terrestrial value and is strongly supportive of assigning the O isotopes found in refractory minerals and inclusions to the Sun. The complexities of the Solar wind make a more precise and detailed conclusion difficult. No spectral data on O in the Sun are sufficiently precise to directly establish the Solar value.

If one takes the O in refractory minerals and CAIs to represent that of the infalling material during formation of the Sun, then we infer that if the O isotopes and $^{26}Al/^{27}Al$ were both uniform at some time in the placental molecular cloud from which the Sun formed, then the implication is that we are sampling infall over a time of ~3My. The questions then become: What is the expected infall rate? How long can infall last? Can some of the infalling parcels be sufficiently heated? When are grains stored in the disk so that they can be preserved? Where are the protoplanets stored that were formed from compounds with Solar oxygen? How and when did the ^{16}O poorer oxygen form and alter the bulk material that comprises the terrestrial planets?

With regard to the infall rate, there are a variety of models and observation with effective rates ranging from $\sim5\times10^{-3}$ $M_\odot$/yr [14] to 3×10^{-8} $M_\odot$/yr [15], and 2×10^{-6} to $\times10^{-5}$ $M_\odot$/yr during FU outburst [16]. The very rapid rates permit the preservation of short-lived nuclei in early formed and stored debris. Whatever the bulk infall rates are for making up about a solar mass, the termination of infall need not be a sharp cut off but could very plausibly come to a slow down and diminished to insignificant level. The kinetic energy of infalling material is very great and would correspond to $\sim10^4$ cal/g. If only a small fraction of infalling material is shock heated upon entering the inner solar system and the condensates preserved in the disk, then the resulting relationship between $^{26}Al/^{27}Al$ and solar O isotopes would be precisely that which is measured.

We conclude that the straightforward interpretation of the $^{26}Al/^{27}Al$ and oxygen isotopic data in refractory minerals and CAIs is compatible with rapid infall along from a simple source originally uniform at some point in time in $^{26}Al/^{27}Al$, $^{18}O/^{16}O$, $^{17}O/^{16}O$ with a slow tailing off of infall (~3 Ma) with some form of shock heating. No late injection or multi-component ^{26}Al source is required. The very low initial $^{26}Al/^{27}Al$ ratios in some refractory minerals and CAIs are then late formed condensates instead of early formed prior to the injection of ^{26}Al.

There remain many issues that must be resolved. These include the apparent absence of planetary bodies with solar oxygen isotopic composition. One possibility is that objects (over 0.5 Km) would be completely disrupted due to internal heating for $^{26}Al/^{27}Al > 2\times10^{-5}$.

If the arguments presented for variable and slow late infall are correct, then the $^{26}Al/^{27}Al$ chronometer should be reliable.

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