THE OXYGEN ISOTOPE EVOLUTION OF OUR GALAXY: IMPLICATIONS FOR THE INTERPRETATION OF EARLY SOLAR SYSTEM HETEROGENEITIES.

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Introduction: The three isotopes of oxygen (^{16}O, ^{17}O and ^{18}O) are produced by different nucleosynthetic processes. The major isotope, ^{16}O, is produced in supernovae and is the most abundant product of primary galactic nucleosynthesis. The two more abundant elements, H and He, were produced by the Big Bang nucleosynthesis. Clayton et al. [1] discovered large, mass independent variations in ^{16}O relative to both ^{17}O and ^{18}O in primitive meteorites. Solar System oxygen is now known to be isotopically heterogeneous on all spatial scales, from sub-micron-sized grains to planets. The origin of this isotopic heterogeneity is still unresolved. The lack of correlated nucleosynthetic anomalies in isotopes of major elements such as Mg and Si along with the lack of ^{16}O-pure presolar grains lead Clayton [2] to abandon the original idea that the mass independent fractionation line results from mixing with a ^{16}O pure supernova end member. The current favorite mechanism for explaining the mass independent fractionation of O isotopes in primitive meteorites is self-shielding of carbon monoxide during UV photo dissociation at different astrophysical settings [2, 3, 4]. Here we describe a simple galactic evolution model for producing and preserving the observed mass-independent oxygen isotope variations in solar system materials.

Condensation of Oxygen: Condensation from a gas of average galactic composition produces three major oxygen reservoirs relevant to this study: (1) high-temperature Al, Ca, Ti-enriched refractory phases (~ 1 % of total O) commonly referred to as CAIs, (2) a 'silicate dust' (~ 14 % of total O) consisting mainly of ferromagnesian silicates, olivine and low-Ca pyroxene, and products of their hydration formed in the mid-and low-temperature range, and (3) the residual gas enriched in H, He, O, C, and N (~86 % of total O), with the last three elements capable of condensing as ices at very low temperatures. Because stellar nucleosynthesis led to predictable changes in the average Galactic elemental abundances with time [5], it is instructive to study whether and how such changes would affect the partitioning of O among different reservoirs. Figure 1 shows the condensation curves of oxygen from a gas of galactic average composition at 100 Ma, 1 Ga and 10 Ga (time of Solar System formation) after the Galaxy formation. These were calculated at total pressure of 10^{-4} bar using ZONMET [6]. The calculation at 10 Ga uses the composition of the Solar System [7] while for earlier times the average Galaxy compositions were obtained from [5]. The overall condensation trend of O

remains the same; a shift of condensation curves to higher temperatures as the Galaxy gets older is due to the increase of 'metal'/H+He ratio with time.
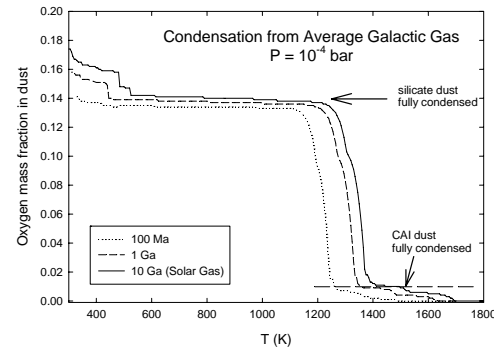

Figure 1. Condensation of oxygen from gases of galactic average composition at 100 Ma, 1 Ga and 10 Ga (Solar System formation) after galaxy formation.

Galactic Evolution: For a simple model of uniform production of ^{16}O (p_{16}) we have $d^{16}O/dt = p_{16}$ and the amount of ^{16}O will increase linearly with time over the history of our Galaxy ($^{16}O_{Total} = p_{16}t$). Oxygen is unique among all the elements in that it is present in significant quantities in both the dust and the gas of the diffuse interstellar medium. We investigate this problem using a simple two-box model approach (Fig. 2).
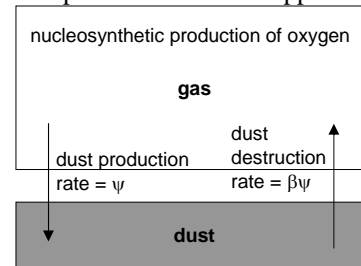

Figure 2. Galactic evolution model for oxygen isotopes.

In this model, at any time after time 0 oxygen is partitioned between the dust and gas: $^{16}O_{Total} = {}^{16}O_{gas} + {}^{16}O_{dust}$. We assume that all nucleosynthetically produced ^{16}O first enters the gas reservoir, but shortly thereafter upon cooling some of the new ^{16}O is locked up in dust. The rate of growth of ^{16}O in the dust reservoir is thus a balance between the rate of dust formation (ψ) and dust destruction ($\beta\psi$). For uniform production, the rate of growth of ^{16}O in the galaxy is thus given by:

$$^{16}O_{dust}(t) = \frac{\psi p_{16}}{a^2}\left[at - 1 + \exp(-at)\right]$$

where $a = (\beta+1)\psi$. The model assumes that oxygen isotopes are produced by galactic nucleosynthetic injec-

tions into the gas phase of the interstellar medium. Some of this oxygen is locked up in dust grains (at a rate proportional to the amount of ^{16}O in the gas) which may later be destroyed by various processes in the interstellar medium. The dust reservoir may thus preserve a component of older galactic oxygen compared to the oxygen in the gas. The mass fraction of ^{16}O in the dust is: $^{16}x_{dust} = {}^{16}O_{dust}/{}^{16}O_{Total} = [1-\exp(-(\beta+1)\psi t)]/(1+\beta)$. It is assumed that a steady state distribution of oxygen is established between the gas and dust of the interstellar medium (in this case $^{16}x_{dust} = 1/(1+\beta)$). We note that during condensation, silicate dust consumes about 14% of solar oxygen ($^{16}x_{dust} = 0.14$ and $\beta = 6.1$), with only ~1% being locked up in CAIs (for CAI-dust: $^{16}x_{dust} = 0.01$ and $\beta = 99$).

In contrast to ^{16}O, ^{18}O and ^{17}O are products of secondary nucleosynthesis [8] with their yields being approximately proportional to the existing galactic inventory of ^{16}O and ^{12}C and must follow: $d^{18}O/dt = \alpha_{18}(^{16}O_{Total}) = \alpha_{18}p_{16}t$ where α_{18} is the proportionality factor. Thus, for a uniform production model of ^{16}O, the inventories of ^{17}O and ^{18}O are expected to have a squared dependence of time: $^{18}O_{Total} = \alpha_{18}p_{16}(t^2/2)$. This results in a linear increase of $^{17}O/^{16}O$ and $^{18}O/^{16}O$ over the history of our Galaxy. For secondary isotopes such as ^{17}O and ^{18}O, the isotope ratio for the total system is: $(^{18}O/^{16}O)_{Total} = [\alpha_{18}p_{16}(t^2/2)]/(2p_{16}t) = \alpha_{18}t/2$ where $\alpha_{18} = (2/T^*)(^{18}O/^{16}O)_{Total} = 0.0004$ Ga^{-1} and $T^* = 10$ Ga. From the resulting ^{18}O evolution, the isotope ratio evolution in the dust is:

$$\left(\frac{^{18}O}{^{16}O}\right)_{dust} = \frac{\frac{\alpha_{18}}{a}\left[1 - at + \left(\frac{1}{2}\right)a^2t^2 - \exp(-at)\right]}{[at - 1 + \exp(-at)]}$$
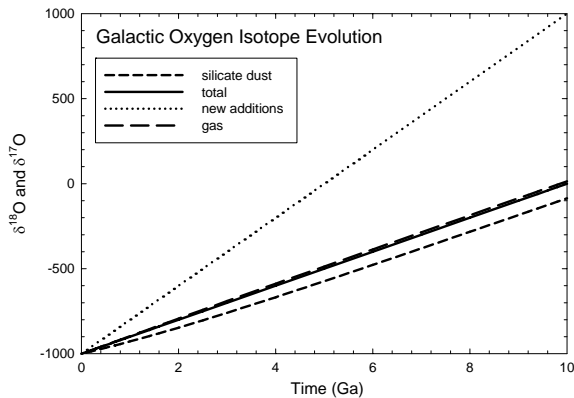
Figure 3. The evolution of oxygen isotope ratios (shown as δ-values relative to the average solar composition) as a function of time. The average galactic evolution is labeled "total". For these calculations we assumed a difference between the gas and the dust of 100 per mil that results in a residence time of oxygen in the dust of 1.1 Ga. The dotted curve is for new nucleosynthetic additions to the interstellar medium as a function of time.

The residence time of oxygen in the dust is: $\tau = 1/\beta\psi$ and $a = (\beta+1)\psi = (\beta+1)/\beta\tau$. The evolution of oxygen isotope ratios in various reservoirs as a function of time from 0 to 10 Ga is shown in Fig. 3. Both ^{17}O and ^{18}O ends up at a value of +1000 per mil at the time of formation of the Solar System. This is the expected average value of new additions to the ISM at the time of formation of our Solar System; it differs greatly from the average ISM material from which the Solar System was derived.
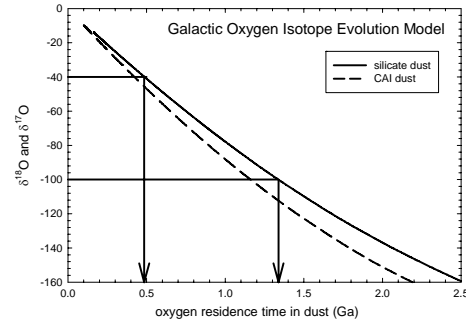
Figure 4. Relationship between δ^{17}O and δ^{18}O (δ relative to solar oxygen isotope ratios) in the dust and the mean oxygen residence time in the dust.

Conclusions: An approximate solution for the value δ$^{18}O_{dust}$ at the origin of the Solar System is: $= [(2-at)/(a^2t^2-at)]10^3$. The box-model gives a simple relationship between δ^{17}O and δ^{18}O (δ relative to the solar oxygen isotope ratios) and the mean oxygen residence time in the dust, shown in Fig. 4. The δ^{17}O and δ^{18}O difference between the dust and gas must be at least about 50 per mil to generate the range of values observed in primitive meteorites. Ireland et al. [9] recently reported a best estimate of the present solar value of about +50 per mil. This means that the difference between the initial dust and gas in the Solar System could be as large as 100 per mil. Since δ^{17}O and δ^{18}O values in the dust must be in the range of -40 to -100, our model suggests a mean residence time of the oxygen in the dust of 0.5 to 1.3 Ga (Fig. 4). Such a lifetime is reasonable for the coarse dust in the interstellar medium [10]. Thus, the basic conclusion is that a simple galactic evolution model can easily account for the observed variations of oxygen isotopes in primitive meteorites.

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