OXYGEN ISOTOPE RESERVOIRS DURING STAR FORMATION AND IN THE SOLAR NEBULA.

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Introduction: The oxygen isotope ratios $\delta^{18}O$ [= $(^{18}O/^{16}O) / (^{18}O/^{16}O)_{STD} - 1$, measured in parts per thousand], and $\delta^{17}O$ have long been used to characterize meteoritic materials. The quantity $\Delta^{17}O = \delta^{17}O - (0.518 \times \delta^{18}O)$ corrects for mass-dependent isotopic fractionation and is diagnostic of the reservoirs meteoritic components formed from. Understanding these isotopic reservoirs and how they arose would allow identification of the times and places in the protoplanetary disk where different inclusions formed, but many details are not yet understood. Here we combine astrophysical modeling with meteoritic constraints on oxygen isotopic ratios and oxygen fugacities, presenting a new quantitative model of these reservoirs.

Our Model: Following others [1], we hypothesize that the main oxygen reservoirs were H_2O ice, CO gas, and silicates. We assign f_{H2O}=50% of O atoms in the molecular cloud to H_2O, f_{CO}=33% to CO, and f_{SIL}=17% to silicates, and assume their isotopes were homogenized in the interstellar medium, with $\Delta^{17}O$ = 0‰. We assume isotopically selective self-shielding of CO photodissociation destroyed about 15% of all $C^{17,18}O$ molecules in the molecular cloud, yielding CO with f_{CO}=28% and $\Delta^{17}O$ = -167‰, and H_2O with f_{H2O}=55% and $\Delta^{17}O$ = +85‰, matching the water invoked for the cosmic symplectite in Acfer 094 [2]. If the solar nebula acquired these equally, the Sun would have $\Delta^{17}O$ = 0‰, but small dust grains are generally held back by magnetic fields during star formation, by up to 60% depending on the magnetic field strength [3]. We assume a plausible 43% of the solids mass was held back. Thus all the CO, but only 57% of the H_2O (ice) and silicates, was accreted, and the solar nebula formed with: CO with f_{CO}=40.6%, $\Delta^{17}O$ = -167‰; H_2O with f_{H2O}=45.4%, $\Delta^{17}O$ = +85‰; and silicates with f_{SIL}=14%, $\Delta^{17}O \approx$ 0‰. The Sun would then have $\Delta^{17}O$ = -29.1‰, consistent with the *Genesis* result $\Delta^{17}O$ = -28.4 ± 3.6‰ [4; see also 5].

Ca-rich, Al-rich inclusions (CAIs) formed from minerals that condensed at temperatures ~1400 K, in a region where CO and H_2O vapor isotopically equilibrated, forming gas with $\Delta^{17}O \approx$ -34.0‰. Depending on the local silicates-to-gas ratio, CAI minerals could condense with $\Delta^{17}O$ as low as -34.0‰, consistent with measurements of the most ^{16}O-rich CAIs [5 and references therein]. Minerals condensing where the silicates-to-gas ratio was enhanced by factors 2.75 ± 0.40 would record $\Delta^{17}O$ = -24.6‰ to -22.3‰, the range observed by [5], explaining why CAIs do not reflect the oxygen isotopic composition of the Sun, a curiosity noted by [5].

Oxygen fugacities further constrain the CAI-forming region. The oxygen fugacity f_{O2} at 1500 K is $\log_{10}(f_{O2}/\mathrm{atm}) = -17.19 + 2 \log_{10}[1 - f_{CO}]$, or $\Delta IW = -5.69 + 2 \log_{10}[1 - f_{CO}]$ below the iron-wüstite buffer, insensitive to temperature. For solar gas at high temperature, f_{CO} = 0.50 [6], and ΔIW = -6.29. CAIs recorded $\log_{10}(f_{O2}/\mathrm{atm})$ = -19.5 ± 0.7 (at 1500 K) [7], or ΔIW = -8.00 ± 0.70, implying much more reducing conditions in the CAI-forming region than the solar nebula overall, especially if the silicate-to-gas ratio was enhanced over solar. An enhanced carbon-to-gas ratio (2.55 -0.35 /+0.17)× the solar ratio of C/H_2 ~5.8 x 10^{-4} [6] and silicates-to-gas ratio of 2.75× solar (yielding $\Delta^{17}O$ = -23.4‰), would yield the range of oxygen fugacities observed in CAIs, $\log_{10}(f_{O2}/\mathrm{atm})$ = -19.5 ± 0.7 [7].

Implications: An increased carbon-to-gas ratio is a natural outcome of pebble drift in the solar nebula. In its first ~10^5 yr of evolution, the disk at < 1 AU saw uniform accretion rates (dM/dt) ~ 10^{-8} $M_{\odot}$ yr^{-1}, hence carbon fluxes ~8 M_E Myr^{-1} [8]. The inward drift of solid pebbles is $(dM/dt)_{pebble}$ ~ 40 - 360 M_E Myr^{-1} [9]; if a typical 3.5wt% C, extra C was delivered to the inner disk at rates 1.4 – 14 M_E Myr^{-1}. In steady state, these rates would lead to carbon-to-gas enhancements $\approx 1 + [(dM/dt)_{pebble} (0.035)] / [(dM/dt) (0.0025)] \approx$ 1.2 – 2.7× solar [10]. Pebble fluxes ~290 - 360 M_E Myr^{-1} would create a reduced inner disk matching the f_{O2} sampled by CAIs, which would form from minerals condensed at a "CAI snow line" at $T \approx$ 1400 K, where the silicate-to-gas ratio could be enhanced by factors ≈ 2-3 [11].

This comprehensive model is the first to simultaneously predict the oxygen isotopic compositions and oxygen fugacities under which CAIs and other meteoritic components formed. If successful, it implies: 1) self-shielding operated in the molecular cloud; 2) magnetic fields held back half of all solids during star formation; 3) a substantial amount of carbon was carried into the inner disk by pebble drift; 4) CAI minerals formed at a silicate "snow line".

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