Multiple nebular gas reservoirs recorded by oxygen isotope variation in a spinel-rich CAI in CO3 MIL 090019.

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Introduction: We conducted NanoSIMS O-isotopic imaging of a primitive spinel-rich CAI spherule (27-2) from the MIL 090019 CO3 chondrite. Inclusions such as 27-2 are proposed to record inner nebula processes during an epoch of rapid solar nebula evolution. Mineralogical and textural analyses suggest that this CAI formed by high-temperature reactions, partial melting, and condensation. This CAI exhibits radial O-isotopic heterogeneity among multiple occurrences of the same mineral, reflecting interactions with distinct nebular O-isotopic reservoirs.

Experimental: CAI 27-2 was found in a polished thin section of the MIL 090019 CO3 chondrite and initial characterization was done at the U. of Chicago. The mineralogy and petrography of the CAI was further examined by SEM/EDX elemental mapping and backscattered electron (BSE) imaging with the JSC JEOL JSM-7600F SEM. These studies revealed a core-to-rim mineral sequence that was targeted for isotopic imaging with the JSC NanoSIMS 50L ion microprobe [1]. Isotopic images were obtained by rastering a 250 nm Cs^+ primary ion beam over 22 x 22 μm fields of view. Secondary ion images of $^{16}O^-$, $^{17}O^-$, $^{18}O^-$, $^{28}Si^-$, $^{24}Mg^{16}O^-$, $^{27}Al^{16}O^-$, and $^{40}Ca^{16}O^-$ were acquired simultaneously in multidetection mode with EMs at a mass resolution of ~10,000 for $^{16}O^-$. San Carlos olivine, Burma spinel, and Madagascar hibonite were measured as primary isotopic standards. A terrestrial FeO-rich spinel was used as a secondary standard and was analyzed directly before each CAI image was acquired using the same methods. A normal incident e^- gun was applied to mitigate charging of the rastered area. Isotopic and elemental ratios of the various minerals within ion images were determined using software developed at JSC.

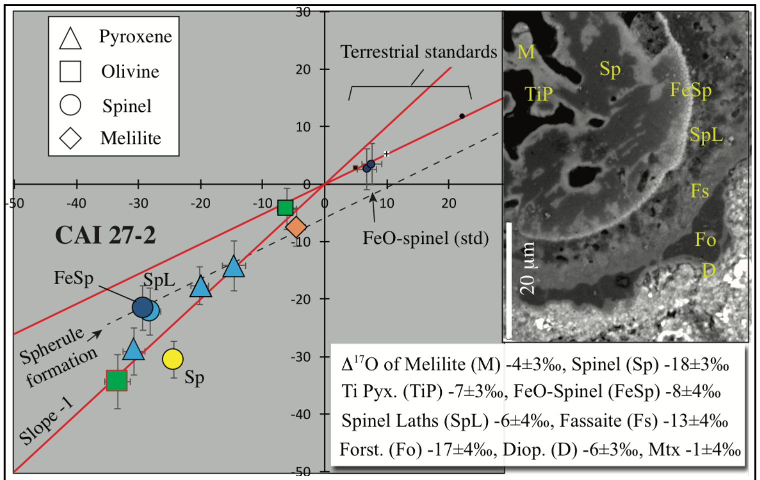

Figure 1. Left: O-isotopes of minerals in CAI 27-2. Silicates lie along slope-1 line, spinel lie above and below. Right: Labeled BSE image of spherule.

Results and Discussion: The CAI core (Fig. 1) consists of Mg-rich spinel, melilite (Ak_{25}), and Ti-rich pyroxene-lined voids. The primary spinel spherule has a thin rind of FeO-rich (30 wt%) spinel that is overlain by a layer of lath-shaped, FeO-poor (≤3 wt%) spinel intergrown with fassaite. A semi-continuous layer of forsterite is located outside the mixed layer, which is surrounded by a thin layer of diopside. The mineral sequence and the multiple occurrences of spinel and pyroxene, in particular the FeO-rich spinel rind that is adjacent to, but inside of, the FeO-poor spinel laths, imply a cyclical formation history involving both reducing and oxidizing gases. The O-isotopic ratios of individual layers are ^{16}O-rich (Fig. 1); melilite (core), spinel (core), pyroxene (core), FeO-rich spinel, FeO-poor spinel laths, fassaite, forsterite, and diopside have $\delta^{18}O$ values of -5, -24, -20, -29, -28, -31, -33, and -15‰, respectively (1σ errors shown).

These observations suggest that 27-2 cycled between ^{16}O-rich and ^{16}O-poor nebular regions as its formation progressed (e.g., [2-11]). O-isotopic compositions of the silicate phases plot along a slope-1 line (Fig. 1), whereas those of the spinel do not. The fact that both mineral types were measured simultaneously suggests that the spinel compositions truly lie off of the slope-1 line. Combining the mineralogical, textural, and O-isotopic observations, we suggest the following formation senario: (1) a spinel-bearing CAI-precursor formed from a ^{16}O-rich gas ($\Delta^{17}O \leq -20$‰); (2) partial melting, condensation, and incomplete exchange occurred with a gas of intermediate composition ($\Delta^{17}O = -6$‰) that formed the spinel spherule, reset the composition of the pyroxene and melilite in the core and created the spinel-lath layer; (3) condensation ±incomplete exchange occurred with a ^{16}O-rich gas ($\Delta^{17}O \leq -20$‰) that formed the forsterite layer; and (4) the diopside layer condensed from the intermediate or similar reservoir ($\Delta^{17}O \geq -6$‰).

References: [1] Ito & Messenger 2008, *Appl. Surf. Sci*. 255, 1446. [2] Clayton et al., 1977, *EPSL* 34, 209, [3] Yurimoto et al. 1998, *Science* 282, 1874 [4] Krot et al. 2002, *Science* 295, 1051 [5] Yoshitake et al. 2005, *GCA* 69, 2663 [6] Aleon et al. 2007, *EPSL* 263, 114, [7] Ito et al. 2010, *LPSC*, Abst.#1177, [8] Simon et al. 2011, *Science* 331, 1175, [9] Park et al. 2012, *MAPS* 47, 2070, [10] Simon et al. 2016, *GCA* 186, 242, [11] Kawasaki et al. 2017, *GCA* 201, 83.