EXTREME OXYGEN AND MAGNESIUM ISOTOPIC ANOMALIES IN PRESOLAR SPINEL GRAINS FROM THE MURRAY CARBONACEOUS METEORITE.

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Introduction: Presolar spinel grains have been identified in several meteorites by their anomalous O isotopic compositions [1-3] and fall into the four previously defined oxide groups [4]. The majority of these grains, in groups 1-3, are believed to originate in various types of red giant (RGB) and asymptotic giant branch (AGB) stars, while the enigmatic Group 4 grains, characterized by ^{18}O excesses, have been hypothesized to be of a supernova (SN) origin [5].

Magnesium-Al spinel grains allow for relatively precise determination of Mg isotopic ratios, in contrast to previous Mg isotopic measurements in presolar SiC, corundum, and graphite, where Mg is a minor element. Most of the previously measured spinel grains' Mg isotopic compositions, characterized by modest enrichments of ^{25}Mg up to ~150‰, can be explained by nucleosynthetic processes. However, several grains have been reported whose extreme Mg compositions are difficult to explain with current AGB models [1, 6].

We report here O isotopic data on 40 new spinel grains from the Murray carbonaceous (CM2) chondrite and Mg isotopic data of the 28 grains remaining after O isotopic analysis. Several grains have very large $^{25,26}Mg$ anomalies, and one grain has the largest $^{17}O/^{16}O$ ratio ever observed.

Experimental: In collaboration with Cameca, the manufacturer of the NanoSIMS, we have developed an automated, high-mass resolution measurement technique for the rapid analysis of large numbers of well-separated grains, similar to previous systems [7, 8]. For this study, the technique and setup were as follows: an area of typically 20x20 µm^2 was presputtered with a large primary Cs$^+$ beam current, in order to remove surface contamination and implant Cs; an ~1pA, 100nm Cs$^+$ beam was then rastered over the area and secondary ion images of $^{16,17,18}O^-$, $^{24}MgO^-$, and AlO$^-$ were simultaneously obtained; discrete grains were identified and sorted by a particle definition algorithm; isotopic measurements were taken by deflecting the primary beam individually onto each grain; the sample stage was then moved, and the entire process repeated. With automated measurements, it is possible to perform unattended measurements over large areas for several days. An additional advantage of our new technique is full integration into the instrument's acquisition software, in principle allowing for greater measurement flexibility.

For the present study, the "CG" residue of Murray, prepared by physical and chemical separation [9] and consisting of high concentrations of spinel grains (average diameter ~0.5 µm), was used; however, we have also successfully applied the automated technique to SiC grains from Indarch. Following identification as presolar, Auger spectra were taken with the Washington University Auger Nanoprobe of the grains, in order to document their elemental composition and confirm whether they are indeed spinel.

In some cases, high-resolution SEM images indicated that a few particles identified and measured by the automatic system consisted, in fact, of multiple grains. Subsequent removal of surrounding isotopically normal grains, as described in detail in [10], revealed several grains to be significantly more anomalous in O composition than the previous bulk measurements which included nearby grains. This also allowed for future measurements to be contamination free. For the grains in which enough material remained, we measured $^{24,25,26}Mg^+$ and $^{27}Al^+$ in multicollection with an O$^-$ primary beam.

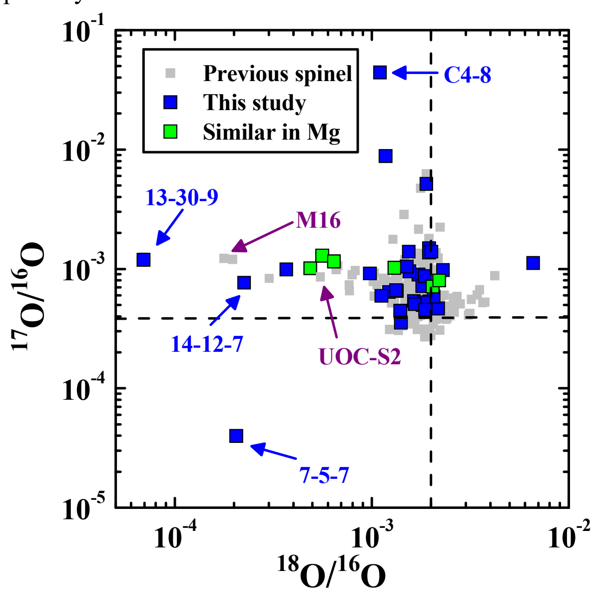

Figure 1. O isotopic ratios of the spinel grains of this study, compared to previous data from references in [11]. The symbol for grain 13-30-9 completely covers the spot where OC2 [3] would plot. The grains plotted as green squares correspond to the grains circled in Fig. 2.

Results and Discussion:

O isotopes. The O isotopic compositions of the presolar grains identified in this study are shown in Fig. 1. The grains fall into all of the four previously identified oxide groups; however, several grains warrant special attention.

Grain C4-8, a group 1 grain, was not identified by the particle definition algorithm – it was embedded in a large clump of other surrounding grains – but rather stuck out in the O isotopic image due to its massive enrichment in ^{17}O. This grain's $^{17}O/^{16}O$ ratio of $4.4x10^{-2}$ is difficult to explain in the context of nucleosynthesis in a single AGB star, AGB stars being the likely source of most group 1 oxide grains. The first dredge-up, when deep convection mixes material that experienced CNO cycling during partial H burning out into the envelope, enhances the star's surface $^{17}O/^{16}O$ ratio. The depth of mixing depends on stellar mass; however, the maximum $^{17}O/^{16}O$ ratio that can be reached is $\lesssim 4x10^{-3}$ for any low-to-intermediate AGB star [12]. Thus, C4-8's O composition cannot be explained by typical dredge-up processes in a single AGB star.

At first glance, grain 7-5-7 appeared to be a typical group 3 grain, characterized by modest depletions in both ^{17}O and ^{18}O. It was later found that what had been measured automatically was, in fact, two grains. After sputtering away the normal grain nearby, grain 7-5-7 was revealed to be highly enriched in ^{16}O and likely to be of a supernova (SN) origin. Interestingly, 7-5-7 has a composition similar to a previously reported SN corundum grain [13] and plots very close to the SN mixing line calculated by [1], resulting from mixing of ^{16}O-rich material with the outermost layers of a SN.

Mg isotopes. Roughly half of the grains measured have essentially solar Mg isotopic composition (Fig. 2), consistent with previous studies [3]. As suggested by [1], this could be due to isotopic exchange in space or on the meteoritic parent body. Alternatively, grains with normal Mg composition could originate either from stars that experienced little or no third dredge-up or from close-to-solar-metallicity RGB stars [3].

All of the remaining grains, except 7-5-7, show large enrichments in ^{26}Mg, up to 1000‰, likely due to the decay of ^{26}Al. For grains having large excesses in ^{25}Mg, such as C4-8 and 14-12-7, it is difficult to deconvolve nucleosynthetic effects from ^{26}Al decay. Six grains show depletions in ^{25}Mg of ~200‰, typically indicative of origin in lower-than-solar-metallicity stars. However, the O isotopic composition (specifically the lack of ^{18}O depletions) of at least 3 of the grains argues for a close-to-solar-metallicity origin. How grains with similar Mg compositions have such dissimilar O isotopes is puzzling, although it may reflect a combination of galactic chemical evolution and nucleosynthesis in the grains' parent stars.

Three of the grains have larger ^{25}Mg excesses ($\gtrsim$ 150‰) than are predicted by standard AGB models, comparable to the extreme compositions of spinel grains M16 [10], OC2 [3], and UOC-S2 [1]. It had been suggested that hot bottom burning (HBB) in an intermediate-mass AGB (IM-AGB) star could explain the O and Mg composition of OC2 [14]. For grains 13-30-9 and 14-12-7 of this study, depleted in ^{18}O and enriched in ^{25}Mg similar to OC2, this origin could also have been a possibility. However, recent reevaluation of the reaction rate of $^{16}O(p,\gamma)^{17}F$ [6], responsible for ^{17}O production by HBB in massive stars, has effectively ruled out IM-AGB stars as the source of these grains. It does seem, though, that many of the most extreme group 2 spinel grains do have substantial Mg anomalies, and that ^{18}O depletions and ^{25}Mg excesses are not entirely decoupled.

Grain C4-8 is unique, as it has a large excess in both ^{17}O and ^{25}Mg, making identification of its parent star even more challenging. The only plausible stellar sites where such extreme isotopic anomalies can be achieved are in novae, in which a nuclear runaway is caused by the accretion of H onto the surface of a white dwarf. In fact, the Mg composition of C4-8 is close to the predictions of [15] for a $0.6M_{\odot}$ CO nova model. Isotopic measurements of other elements in this grain are planned in order to further constrain its origin.

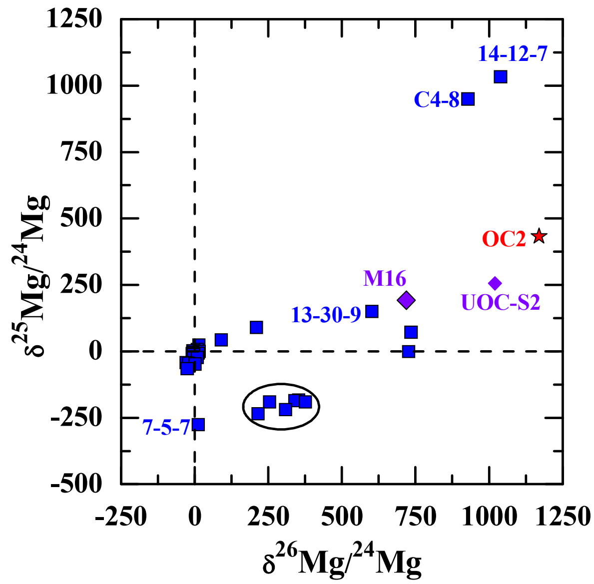

Figure 2. Mg isotopic composition of the grains, expressed as delta values.

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