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Stardust material in the paired enstatite chondrites:

SAH 97096 and SAH 97159

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Stardust grains, more commonly referred to as *presolar grains*, are solid condensates of stars that are studied in terrestrial laboratories with a variety of analytical techniques. Here we report on sub-micrometer silicate, oxide and carbonaceous stardust grains identified in the paired enstatite chondrites SAH 97096 and SAH 97159. A majority of the grains with O isotopic anomalies exhibit ^{17}O excesses and probably originated in the dusty envelopes of low-mass AGB or RG stars. One grain is highly ^{17}O-rich and has a normal Si isotopic composition; based on its O and Si isotopic composition, an origin in a nova is most likely. However, another scenario that may explain this grain's O isotopic composition is a binary star system consisting of an evolved or mainstream star accreting material from its nova companion. Elemental characterization of the O-anomalous grains shows the presence of eleven magnesian silicate grains with or without Fe and three Fe-oxide grains; none of the grains contain Ca or Al. Carbon-anomalous grains have ^{12}C/^{13}C ratios from 19–78; most are probably SiC. The abundances of the O- and C-anomalous grains are 98±34 and 51±13 ppm, respectively, which is much higher than previously observed in other enstatite chondrites, and close to that of some carbonaceous chondrites.

11th Symposium on Nuclei in the Cosmos – NIC XI
Heidelberg, Germany
July 19–23 2010

1. Introduction

Silicate stardust exhibits large O isotopic anomalies and can be found in the form of sub-micrometer sized grains in primitive extraterrestrial materials. These grains survived interstellar processing, heating in the early solar nebula and accretion into parent bodies, as well as possible aqueous alteration, impacts, and thermal metamorphism on those parent bodies. Most searches for silicate stardust grains have been carried out in carbonaceous chondrites [e.g., 1, 2], and much less information is available about silicate stardust in enstatite chondrites. However, these chondrites are of interest because they formed under highly reducing conditions, which may allow the preferential survival of certain types of grains. In addition, comparison of stardust grain abundances in enstatite versus carbonaceous and ordinary chondrites can provide information about conditions in the early solar nebula.

Here we report on the search for stardust grains in the enstatite chondrites, SAH 97096 (100–500 nm grain size-separates) and SAH 97159 (polished thin section) using the Washington University NanoSIMS 50 (secondary ion mass spectrometry) and PHI 700 Auger Nanoprobe. These two meteorites are paired and are among the most primitive EH3 chondrites [3]. A discussion of the analytical techniques used can be found in [4] and [5].

2. Results

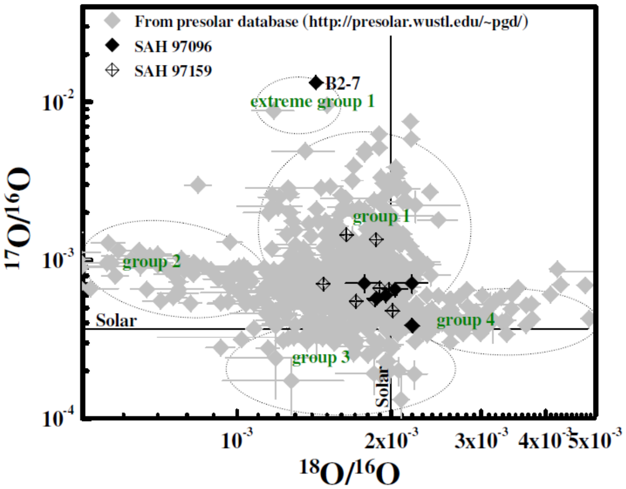

Figure 1: *Oxygen isotopic ratios of presolar oxide and silicate grains from this study (black symbols) and grains from the presolar grain database (gray symbols). Ellipses indicate the O-isotopic groups defined by [5, 7]. Errors are 1σ.*

We identified eight O-anomalous and four C-anomalous grains by ion isotope searches on 14,400 μm^2 of dispersed grains from SAH 97096. In SAH 97159, where we measured a total matrix area of 10,800 μm^2, we found eight O-anomalous grains and fifteen C-anomalous grains. Of the sixteen O-anomalous grains (Table 1), thirteen grains have enrichments in ^{17}O and are largely normal in their ^{18}O/^{16}O ratios while two grains show enrichments in ^{18}O (Figure 1). One grain, B2-7, exhibits a large enrichment in ^{17}O with a ^{17}O/^{16}O ratio of (1.33±0.01) × 10^{-2}, and an ^{18}O/^{16}O ratio of (1.43±0.04) × 10^{-3}. The Si isotopic composition of B2-7 is δ^{29}Si = 21±56 ‰ and δ^{30}Si = 57±69 ‰, i.e., normal within 1σ. The eighteen C-anomalous grains have ^{12}C/^{13}C ratios that range from 19 to 78. Auger Nanoprobe analyses of SAH 97159 were complicated by extensive sample charging issues and the Auger spectra will only be discussed qualitatively. However, because the grain size-separates from SAH 97096 were deposited on Au foil, we did not have similar charging issues with these grains. All the O-anomalous grains in SAH 97159 are ferromagnesian silicate grains; two grains are Fe-rich. Three of the O-anomalous grains from SAH 97096 are silicate grains and three are Fe-oxides. Grain E20-33 has an (Fe+Mg)/Si ratio of 1.2±0.2 suggesting that it has a pyroxene-like stoichiometry. Grains D-1 and 3-7 from SAH 97159 are Si-rich, as is grain E5-112 from SAH 97096; this grain contains no Mg and has 21±2 at.% Fe. Grain B2-7 is 460×400 nm^2 in size and contains more Mg than forsterite. Calcium and Al are below detection in all grains (~3 at.%).

Among the C-anomalous grains, six grains were characterized as SiC based on the presence of C and Si peaks in their Auger spectra. The remaining C-anomalous grains were either sputtered away at the end of the NanoSIMS measurements or could no longer be located.

3. Discussion

3.1. Isotopic Compositions

The O isotopic compositions of the presolar oxide and silicate grains found in SAH 97096 and 97159 fall within the range of presolar oxide groups [6]. Thirteen grains have ^{17}O-rich compositions consistent with a group 1 classification and are likely to have originated in low-mass RG or AGB stars (~1.1–2.5$M_{\odot}$) with close-to-solar or slightly lower-than-solar metallicity [6]. Two grains are ^{18}O-rich and belong to group 4; these grains may have Type II supernova origins, as suggested by [6]. Grain B2-7 has O and Si isotopic compositions similar to other "extreme group 1" grains that have been identified in Acfer 094 [7, 8], and that may be nova condensates. For example, the ^{17}O-rich composition and normal Si isotopic ratios of an extreme group 1 silicate from Acfer 094 can be explained by nucleosynthetic models of a 0.8$M_{\odot}$ CO nova [8]. However, much larger ^{25}Mg isotopic anomalies are predicted by this CO nova model, than are seen in this grain. Furthermore, ONe nova models can *qualitatively* account for the observed O and Si isotopic signatures of three additional extreme group 1 silicates but a quantitative comparison reveals large discrepancies [7]. In these cases, grain formation in binary star systems, where material is transferred from a nova explosion to a main sequence star or an evolved star, has been suggested [6, 9]. A similar formation scenario for grain B2-7 is likely.

The ^{12}C/^{13}C isotopic ratios of the C-anomalous grains reflect compositions similar to mainstream SiC grains, which make up 93% of the SiC grain population [10]. These mainstream SiC grains probably originate in C-rich AGB stars [10].

Table 1: Oxygen isotopic compositions of the silicate and oxide stardust grains

Grains in	**O-Isotopic ratios**	
SAH 97096	**^{17}O/^{16}O (×10^{-4})**	**^{18}O/^{16}O (×10^{-3})**
E5-112	5.8±0.4	1.87±0.08
B2-7	133±1	1.43±0.04
B2-1	3.9±0.2	2.20±0.04
E20-33	6.0±0.6	1.95±0.10
E20-36-tp	7.1±0.9	2.19±0.16
E20-36-bm	6.5±0.7	2.03±0.11
B2-10†	3.9±0.2	2.19±0.04
E20-34†	7.1±0.9	1.77±0.14
SAH 97159	**^{17}O/^{16}O (×10^{-4})**	**^{18}O/^{16}O (×10^{-3})**
3_1	4.8±0.2	2.01±0.01
3_4	7.1±0.3	1.47±0.02
3_7	5.6±0.2	1.96±0.01
B-8-1	14.5±0.2	1.64±0.02
B-8-2	6.6±0.2	1.90±0.01
D-1	6.6±0.2	1.98±0.01
D-6	5.5±0.2	1.71±0.01
E-4-2	13.5±0.6	1.87±0.05

Notes: Grains gone after NanoSIMS measurements are marked by †. Errors are 1σ.

3.2. Fe-rich Elemental Compositions

Three silicate grains in our inventory have Fe-rich compositions, like presolar silicates identified in some carbonaceous chondrites [e.g., 1, 2]. Based on equilibrium condensation calculations, Mg-rich phases are suggested to form at high-temperatures while the formation of Fe-containing phases is inhibited [11]. Iron-rich grains can condense either at low temperatures (~700K) or under non-equilibrium conditions [12], wherein a rapid fall in temperature allows the incorporation of Fe in the silicate grains. Iron can also be introduced by secondary processes in the parent body or on Earth. For example, thermal metamorphism in the meteorite parent bodies can lead to the introduction of Fe, via diffusion, into grains with low Fe contents [13]. Incorporation of Fe into silicate grains may also occur in the nebular environment during gas-grain interactions. Mineral composition studies of SAH 97096 and its pairs show that these EH3 chondrites have experienced little parent body metamorphic heating [e.g., 14]. Although little is known about the temperatures experienced by these meteorites prior to accretion, diffusion is slow during gas-grain interactions at low temperatures in a solar composition gas [15], which may largely prevent the diffusion of Fe into silicate grains. Furthermore, alteration during the meteorite's residence time on Earth may lead to the loss of Mg and/or Si, and result in Fe-rich silicate grains [e.g., 16]. However, [14] argues for little terrestrial alteration of the SAH chondrites studied here based on Ar and Ne cosmic ray exposure ages. The high Fe contents observed in the silicate stardust grains therefore may primarily arise due to formation under non-equilibrium conditions in the outflows of young and evolved stars; secondary processing has probably contributed only to a small extent.

3.3. Comparison between Chondrite Classes: Abundance Estimates and Elemental Compositions

Abundance calculations on grain size-separates (i.e., SAH 97096) are difficult to carry out because of the large errors involved in determining the mass fraction of the separates. However, the abundances of presolar silicate and carbonaceous grains determined in the thin section of SAH 97159 are 98±34 and 51±13 ppm, respectively. The abundance of O-anomalous grains from this work is higher than that found in other enstatite [e.g., 17] and ordinary chondrites, and is close to that of some carbonaceous chondrites (Figure 2). The lack of presolar silicates in SAH 97072, which is paired with SAH 97159/97096, may be due to analytical differences [17]. The abundance of O-anomalous grains in the paired SAH chondrites studied here is somewhat lower than in the most primitive carbonaceous chondrites. Other enstatite chondrites (Figure 2) also exhibit low abundances of O-anomalous grains. It has been argued that the material that accreted to form the enstatite chondrites has experienced nebular thermal processing [e.g., 18]. Calcium-aluminum-rich inclusions in SAH 97159 are highly altered [19] and exotic FeO-rich silicates show evidence for reduction [20]. These effects, as well as the low presolar silicate abundances, may be a result of such nebular processing.

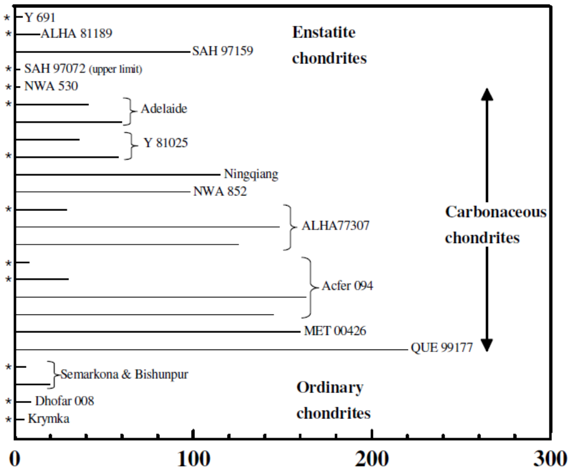

Figure 2: *Bar graph showing the matrix-normalized abundances (ppm) of presolar silicate grains in various chondrites. Those marked with an asterisk are samples measured using the IMS 1270 with a SCAPS detector.*

Our abundance estimate for C-anomalous grains is similar to presolar SiC abundances in the CR chondrites (~65 ppm; [1]) indicating that the pre-accretionary thermal processing experienced by the SAH chondrites has not destroyed these more refractory carbonaceous stardust grains.

The presolar silicate grains identified in the enstatite chondrites have similar elemental compositions as those observed in other carbonaceous chondrites [1, 2]. However, the silicate/oxide grain ratio of ~4 in the SAH chondrites is lower than that observed in a few carbonaceous chondrites (e.g., ~11 in Acfer 094 [2] and 53 in QUE 99177 and MET 00426, combined [1]). Silicate grains may have been destroyed as a consequence of thermal processing [18].

4. Conclusions

Our data show that a significant fraction of stardust grains have survived the thermal episode(s) in the nebular environment experienced by and recorded in the material that accreted to form the enstatite chondrites. Abundances of stardust phases in the enstatite chondrites studied here are higher than previously reported and are close to what has been observed for some carbonaceous and ordinary chondrites. Observations of high Fe contents in the silicate grains suggest that kinetics play a key role in the condensation of dust grains in stellar outflows, as discussed by [2].

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