PRESOLAR GRAPHITE FROM THE MURCHISON METEORITE: PUZZLES RELATED TO ITS ORIGINS.

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Introduction: Presolar graphite grains are present in primitive meteorites and those extracted from Murchison and Orgueil have been extensively studied [1-6]. One of their most intriguing features is that isotopic, elemental and morphological features depend on density. Four Murchison fractions with a range of density, KE3 (1.65-1.72 g/cm^3), KFA1 (2.05-2.10 g/cm^3), KFB1 (2.10-2.15 g/cm^3) and KFC1 (2.15-2.20 g/cm^3), have been separated [3, 7]. We discuss outstanding issues related to the origin of Murchison graphite grains.

Discussion: Amari et al. [8] classified graphite grains based on their ^{12}C/^{13}C ratios. Grains with ^{12}C/^{13}C < 20 were classified as Population I, those with 20 ≤ ^{12}C/^{13}C ≤ 200 as Population II, and those with ^{12}C/^{13}C > 200 as Population III.

KE3 and KFA1 grains. Many KE3 and KFA1 grains show signatures of an origin in core-collapse supernovae, where different nucleosynthetic processes take place in different zones before the explosion [4]. Oxygen-18 excesses in many grains reflect alpha-capture on ^{14}N in the He/C zone. High ^{26}Al/^{27}Al ratios are produced in the He/N zone via the ^{25}Mg(p,γ) reaction (Fig. 1). Silicon isotopic anomalies, mainly ^{28}Si excesses, but also excesses in ^{29}Si and ^{30}Si, indicate O-burning and neutron capture reactions, respectively. The initial presence of ^{44}Ti in a few grains is a definite proof of a supernova origin because ^{44}Ti is produced only during explosive nucleosynthesis. Thirty-seven percent of KE3 grains in Population I, 84 % of those in Population II and 82 % of those in Population III show ^{18}O excesses, while 29 % of KFA1 grains in Population I, 56 % of those in Population II and 11 % of those in Population III do. According to these numbers, Population II hosts many supernova grains. In the 15M$_{sun}$ SN model by Rauscher et al. [9], the ^{12}C/^{13}C ratio of the He/C zone is predicted to be 2 × 10^5 and that of the He/N zone to be 4. Although a wide range of ^{12}C/^{13}C ratios, including ratios between 20 and 200, can be reproduced by mixing these two zones with the extreme ^{12}C/^{13}C ratios, the presence of many supernova grains in Population II indicates that zones with ^{12}C/^{13}C ratios between these extremes might have taken part in the mix from which the grains formed. A candidate is the H-rich envelope with the ^{12}C/^{13}C ratio of 17 and/or material in the stellar wind with the ^{12}C/^{13}C ratio of 22, comparable to that of the H-rich envelope.

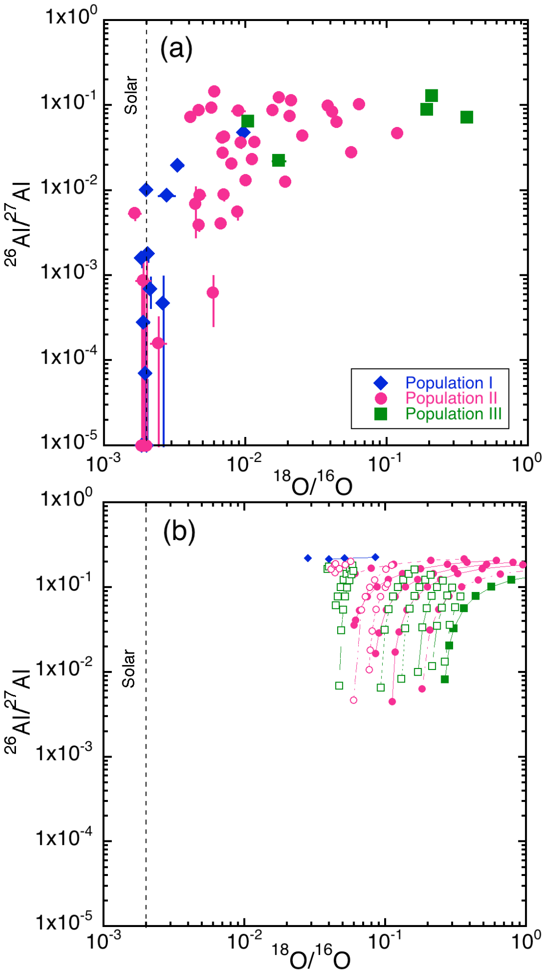

Fig. 1. Aluminum and O isotopic ratios. (a) KE3 grains and (b) mixing calculations of supernova zones [9]. Blue, magenta and green symbols indicate the carbon isotopic ranges of Population I, II and III, respectively.

We performed mixing calculations of the He/C, He/N zones and the H-rich envelope to reproduce the observed isotopic ratios. Since we have evidence that elemental fractionation takes place in supernova ejecta [10], we focus on a few elements that might have been least affected by elemental fractionation. Carbon is the major element. Oxygen is critical for carbon grain formation. Aluminum is refractory and relatively abundant in graphite, and ^{26}Al is a signature of the He/N zone.

Fig. 1 (a) shows the grain data, while (b) results of mixing calculations. Assuming C>O is required to form graphite grains, we mixed three zones (He/C, He/N and H-rich envelope, results shown with solid symbols), as well as four zones (these three and O/C, shown with open symbols) of a 15M_{sun} star [9]. For a given track in Fig. 1 (b) the mass fraction of the He/C zone as well as that of the O/C zone for the four-zone mixing is kept constant while the relative fractions of the other zones are changed. The isotopic ratios of grains from Population III can be explained with the mixing. However, the isotopic distributions of Population II, and especially Population I, cannot be reproduced.

Since the ^{18}O content of the He/C zone is so high (4 × 10^{-3} in mass fraction), a significant amount of ^{16}O is needed to lower the ^{18}O/^{16}O ratio, but this makes the mix O-rich. The situation is worst for Population I grains. Only a small amount of material from the He/C zone can be in the mix to reproduce their low ^{12}C/^{13}C ratios. Even with this small amount of material from the He/C zone, the ^{18}O/^{16}O ratios of the mix are still >10^{-2}, and ^{16}O from other zones cannot lower the ^{18}O/^{16}O ratios if we keep C-rich conditions.

It has been proposed that carbonaceous grains can form in a O-rich supernova environment [11]: abundant and stable CO molecules are dissociated by energetic electrons produced by Compton scattering of gamma-rays from ^{56}Co ($T_{1/2}$ = 77 d), making C available for graphite formation. However, it remains to be seen if this is indeed the case.

KFB1 and KFC1 grains. KFB1 and KFC1 grains have similar distributions of ^{12}C/^{13}C, with a pronounced peak centered at ~ 400 – 500. These high ratios are indicative of low-metallicity asymptotic giant branch (AGB) stars. Bulk noble gas analysis indicates that KFC1 grains originated in low-metallicity stars (Z ≤ 0.002) [12]. TEM studies of slices of KFC1 grains found subgrains that are highly enriched in s-process elements, confirming that KFC1 grains formed in low-metallicity AGB stars [13, 14]. Noble gas analyses of single KFB1 and KFC1 grains also provided evidence that some of the grains originated from low-metallicity AGB stars [15, 16].

With updated model calculations of low-metallicity AGB stars, we reexamined s-process Kr in KFC1. ^{86}Kr/^{82}Kr ratios are sensitive to nucleosynthetic conditions because there is an s-process branching in ^{85}Kr, which decays to ^{85}Rb with the half-life of 11 years. Thus ^{86}Kr/^{82}Kr ratios depend on neutron density. Amari et al. [17] derived the s-process ^{86}Kr/^{82}Kr ratio to be 4.43 ± 0.46 (shown in the red shaded area in Fig. 2), assuming for s-process ^{83}Kr/^{82}Kr = 0.375. Two cases agree with the inferred ratio: $M = 3M_{sun}$, $Z = 3 \times 10^{-3}$ and $M = 5_{sun}$, $Z = 1 \times 10^{-2}$. The former can also account for the C isotopic distribution of many grains in KFC1. However, when we consider the Kr bulk data and C isotopic ratios of single grains, they do not have to point the same source: the s-process Kr may be carried by only a handful grains. Therefore, from these data alone, we cannot determine which is a more likely source of the Kr.

Another observation that has to be explained is that KFC1 and KFB1 have similar C isotopic distributions but completely different s-process ^{86}Kr/^{82}Kr ratios [12]. Closer inspection shows that KFB1 contains fewer grains with ^{12}C/^{13}C between 90 and 170 and > 1000. If grains with these C isotopic ranges carry the s-process Kr in KFC1, the difference and similarity between KFC1 and KFB1 can be reconciled.

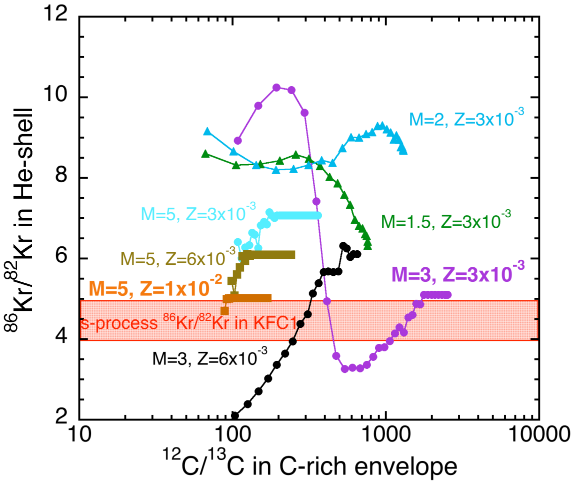

Fig. 2. Model calculations of s-process ^{86}Kr/^{82}Kr in the He-shell of AGB stars and ^{12}C/^{13}C in the C-rich envelope for stars with various masses and metallicities The red shaded area indicates the s-process ^{86}Kr/^{82}Kr ratio inferred from KFC1.

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