# Abundances of Presolar Graphite and SiC from Supernovae and AGB Stars in the Murchison Meteorite

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**Abstract.** Pesolar graphite grains exhibit a range of densities (1.65 – 2.20 g/cm$^3$). We investigated abundances of presolar graphite grains formed in supernovae and in asymptotic giant branch (AGB) stars in the four density fractions KE3, KFA1, KFB1 and KFC1 extracted from the Murchison meteorite to probe dust productions in these stellar sources. Seventy-six and 50 % of the grains in the low-density fractions KE3 and KFA1, respectively, are supernova grains, while only 7.2 % and 0.9 % of the grains in the high-density fractions KFB1 and KFC1 have a supernova origin. Grains of AGB star origin are concentrated in the high-density fractions KFB1 and KFC1. From the C isotopic distributions of these fractions and the presence of *s*-process Kr with $^{86}$Kr/$^{82}$Kr = 4.43 ± 0.46 in KFC1, we estimate that 76 % and 80 % of the grains in KFB1 and KFC1, respectively, formed in AGB stars. From the abundance of graphite grains in the Murchison meteorite, 0.88 ppm, the abundances of graphite from supernovae and AGB stars are 0.24 ppm and 0.44 ppm, respectively: the abundances of graphite in supernovae and AGB stars are comparable. In contrast, it has been known that 1 % of SiC grains formed in supernovae and 95 % formed in AGB stars in meteorites. Since the abundance of SiC grains is 5.85 ppm in the Murchison meteorite, the abundances of SiC from supernovae and AGB stars are 0.063 ppm and 5.6 ppm, respectively: the dominant source of SiC grains is AGB stars. Since SiC grains are harder and likely to survive better in space than graphite grains, the abundance of supernova graphite grains, which is higher than that of supernova SiC grains, indicates that supernovae proficiently produce graphite grains. Graphite grains from AGB stars are, in contrast, less abundant that SiC grains from AGB stars (0.44 ppm vs. 5.6 ppm). It is difficult to derive firm conclusions for graphite and SiC formation in AGB stars due to the difference in susceptibility to grain destruction. Metallicity of the parent AGB stars of graphite grains is much lower than that of SiC grains and the difference in metallicity might also have affected to the difference in the abundances in the Murchison meteorite.

**Keywords:** graphite, SiC, presolar grains, dust, meteorites, supernovae, asymptotic giant branch stars, ion probe
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## INTRODUCTION

Presolar grains are stardust preserved in meteorites. These grains had formed in stellar outflow or stellar ejecta and were incorporated in the molecular cloud from which our solar system formed. Most grains were destroyed during solar system formation. However, a small portion of the grains survived and remains preserved in meteorites. Presolar grains have been extracted from meteorites using chemicals or they have been located in meteorites and interplanetary dust particles (IDPs) with ion imaging techniques. The abundances of presolar grains range from a few ppb to a few hundred ppm in bulk meteorites. Mineral types identified to date include diamond [1], SiC [2, 3], graphite [4], oxides [5-7], silicates [8-11] and refractory carbides in graphite [12-14] and SiC [15]. The laboratory study of these grains has yielded a wealth of information about nucleosynthesis in stars, mixing in supernova ejecta and Galactic chemical evolution. Details of many aspects of presolar grains studies can be found in various review papers [16-21].

Graphite and SiC grains have been extensively studied by ion probe: many graphite grains are larger than 1 μm and low-density graphite grains show relatively high trace element concentrations such that we are able to carry out multi-element isotopic analysis of individual grains. Although most SiC grains are sub-μm in size [22], grains of a few μm in size exist and their trace element abundances are high [23] compared with those of other mineral types. Isotopic analyses of these grains have revealed that they formed in various types of stars, most notably asymptotic giant branch (AGB) stars and supernovae. These stellar objects are the two main dust producers in the universe. In this study, we focus on graphite and SiC, estimate the abundances of graphite from supernovae and AGB stars in the

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Murchison meteorite (CM2), compare them with those of SiC, and infer dust formation by supernovae and AGB stars.

## GRAPHITE

Presolar graphite grains exhibit a range of density. Four density fractions have been extracted from the Murchison meteorite: 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$^3$) [22, 24]. Figure 1 shows distributions of $^{12}$C/$^{13}$C ratios of grains from these fractions. Grains in the low-density fractions KE3 and KFA1 show broad distributions. Grains in the high-density fractions KFB1 and KFC1 show two distinct peaks, a smaller peak around the $^{12}$C/$^{13}$C ratio of 10 and a larger peak around a ratio of a few hundred. All fractions show a spike at the bin where the solar $^{12}$C/$^{13}$C ratio (89) falls. This sudden increase of the number of grains must be due to the presence of grains of solar-system origin in addition to presolar grains. We estimated the number of presolar grains in the normal bin in each fraction, assuming that presolar grain distributions are smooth. We took the average of the adjacent bins to the normal bin. If isotopic analyses of other elements show higher numbers of grains to be presolar than the average, we took the former. Then we derived the abundances of presolar grains in each density fraction: 0.22, 0.11, 0.13 and 0.42 ppm weight for KE3, KFA1, KFB1 and KFC1, respectively, relative to the bulk Murchison meteorite.

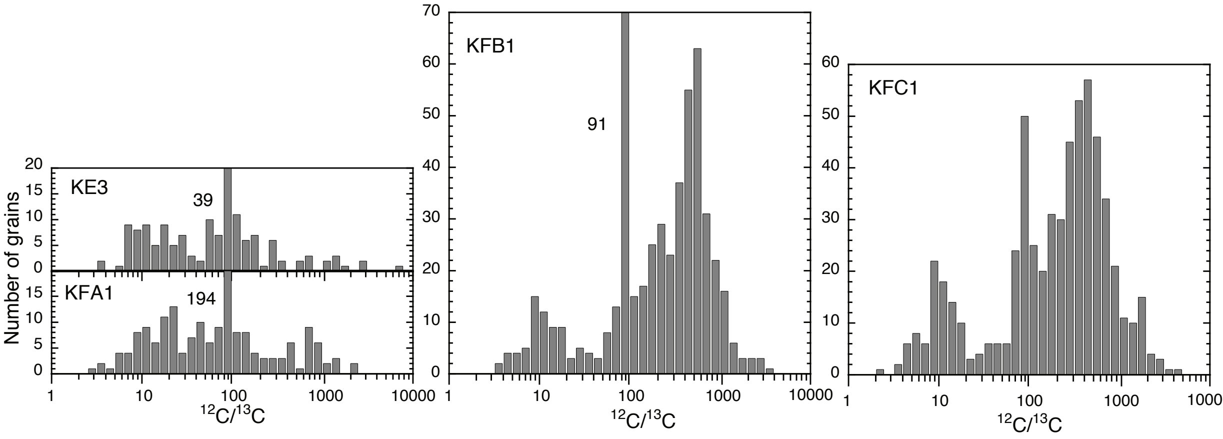

**FIGURE 1.** $^{12}$C/$^{13}$C histograms of grains from the Murchison graphite fractions. The numbers in the figures are those in the normal bin (see text for details).

## Graphite from Core-Collapse Supernovae

One of the most diagnostic features of a supernova origin that is widely seen in graphite grains is $^{18}$O excess. Oxgyen-18 is produced by $^{14}$N($\alpha,\gamma$)$^{18}$F($e^+\nu$)$^{18}$O during partial He burning in the He/C zone. Rauscher et al. [25] predicted the $^{18}$O/$^{16}$O ratio to be 1.68 in the zone in a 15M$_\odot$ star of solar metallicity (s15a28c case). The highest $^{18}$O/$^{16}$O ratio (0.37) and the highest abundance of $^{18}$O-rich grains (70%) are found in KE3. The fraction of $^{18}$O-rich grains in KFA1 is smaller than that in KE3, but is still 42 %. The abundances dramatically decrease in KFB1 and KFC1 to only 4.5 % and 0.8 %, respectively.

There are other isotopic signatures of a supernova origin. The initial presence of $^{44}$Ti in the form of $^{44}$Ca excesses is found in fewer grains. This is proof of grains' supernova origin because $^{44}$Ti is produced only in supernovae during explosive nucleosynthesis. High $^{26}$Al/$^{27}$Al ratios (~ 0.1) are expected when grains contain material from the He/N zone, where $^{25}$Mg(p,$\gamma$)$^{26}$Al takes place. Silicon-28 excess indicates that material from the inner Si/S zone is mixed into the outer zones. Alternatively, $^{28}$Si may be produced in the He/C zone during explosive nucleosynthesis. Pignatari et al. [26] investigated explosive nucleosynthesis in the He/C zone during passage of the shock wave. They found that the rates of successive alpha-capture reactions starting from $^{16}$O producing $^{28}$Si increase at $T > 3.5 \times 10^8$

K, making the bottom of the He/C zone $^{12}C$- and $^{28}Si$-rich. According to their models, there is no need to invoke mixing between the inner Si/S zone and the outer zones. In either case, $^{28}Si$ is a signature of supernovae.

When the grains with isotopic signatures in other elements are included, the fractions of supernova (SN) grains in KE3, KFA1, KFB1 and KFC1 are 76%, 50%, 7.2%, and 0.9%, respectively. From these numbers and the abundances of the density fractions, we derive an abundance of 0.24 ppm of graphite SN grains in the Murchison meteorite.

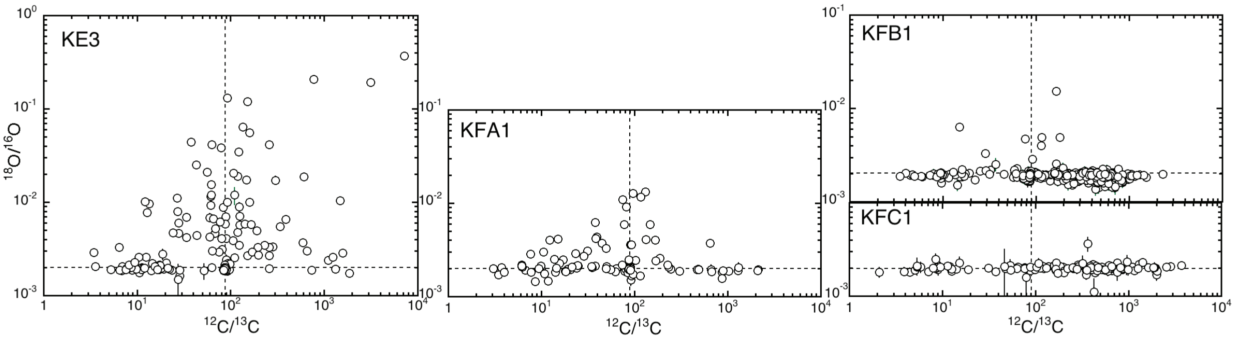

**FIGURE 2.** $^{18}O/^{16}O$ and $^{12}C/^{13}C$ ratios of graphite grains in the Murchison graphite fractions. The dotted lines indicate the solar isotopic ratios.

## Graphite from AGB stars

There exists evidence that KFC1 grains formed in low-metallicity AGB stars. Excesses in $^{29,30}Si$ in a few KFC1 grains indicate that they formed in low-metallicity AGB stars [27]. A peculiar *s*-process Kr with a high $^{86}Kr/^{82}Kr$ (4.43 ± 0.46), only seen in KFC1, has been interpreted as originating from low-metallicity AGB stars [28, 29]. Refractory carbide subgrains with high *s*-process element abundances within KFC1 graphite grains [13, 30] also point to AGB stars of low-metallicity as their sources. Helium and Ne analysis in single KFC1 grains shows that some of the gas-rich grains formed in AGB stars with sub-solar to solar ($Z/Z_\odot$ = 1/6 to 1) metallicities and a few (1.5 – 5) $M_\odot$. Light noble gas analysis of KFB1 grains also identified a grain from a low-mass (1.5 – 2 $M_\odot$) AGB star with sub-solar metallicity [31]. The similarity of the C isotopic distributions (Fig. 1) indicates that KFB1 and KFC1 have similar stellar sources, but the difference in *s*-process Kr between these two fractions [28, 29] suggests that there is a distinct source to produce the Kr found only in KFC1.

Assigning stellar sources for KFB1 and KFC1 grains from the $^{12}C/^{13}C$ ratio distributions of both fractions and the *s*-process Kr in KFC1 (Kr-SH) (Fig. 1) has been described by Amari et al. [32, 33]. We briefly summarize it here. The range of $^{12}C/^{13}C$ ratios of the major peak in KFB1 and KFC1 (Fig. 1) agree with predicted ratios in the envelope of low-mass (1.5 – 3 $M_\odot$) low-metallicity ($Z = 3 \times 10^{-3}$, $Z = 6 \times 10^{-3}$ for $3M_\odot$ stars only) AGB stars (Fig. 3). The *s*-process Kr with a high $^{86}Kr/^{82}Kr$ ratio (4.43 ± 0.46) is only observed in KFC1, but not in KFB1. Such a high ratio is predicted for the He-shell in $3M_\odot$ stars ($Z = 3 \times 10^{-3}$) and $5M_\odot$ stars ($Z = 1 \times 10^{-2}$, $Z = 2 \times 10^{-2}$). Since the Kr is not observed in KFB1, $3M_\odot$ stars ($Z = 3 \times 10^{-3}$), which are likely sources of high $^{12}C/^{13}C$ ratios in both KFB1 and KFC1, are not a source of Kr-SH: sources of grains which exist only in KFC1 should have produced Kr-SH. A close inspection of the C isotopic diagram of KFC1 shows a small bump around $^{12}C/^{13}C = 100$ that does not appear in KFB1. $^{12}C/^{13}C$ ratios in the envelope of $5M_\odot$ stars with $Z = 1 \times 10^{-2}$ and $Z = 2 \times 10^{-2}$ are expected to range from 89 to 169 and from 80 to 108, respectively. If the small bump represents grains from the $5M_\odot$ stars, both the $^{12}C/^{13}C$ ratios of the grains and Kr-SH in KFC1 can be explained.

We assigned an AGB star origin to KFB1 grains with $^{12}C/^{13}C$ ratios ≥ 100 and KFC1 grains with $^{12}C/^{13}C$ ratios ≥ 60, yielding fractions of 76 % and 80 % of grains from KFB1 and KFC1, respectively, to come from AGB stars. We do not see any evidence that part of low-density graphite grains from KE3 and KFA1 formed in AGB stars. The above numbers, together with the abundances of the density fractions, give an abundance of 0.44 ppm weight of the Murchison meteorite for graphite grains from AGB stars.

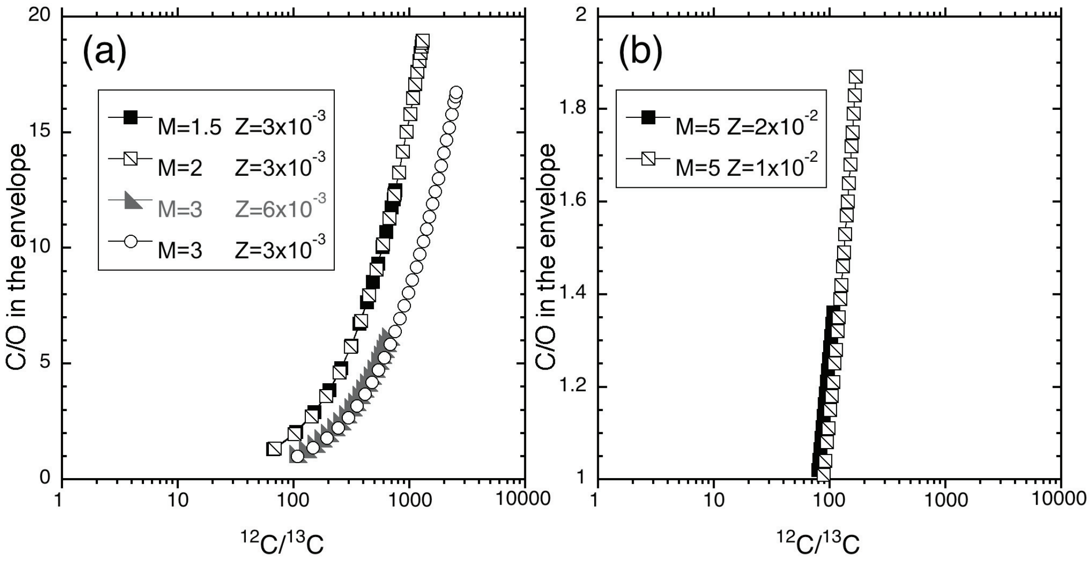

**FIGURE 3.** C/O and $^{12}C/^{13}C$ ratios in the C-rich envelope of models of low-metallicity AGB stars with (a) 1.5 – 3 $M_{\odot}$ and (b) 5 $M_{\odot}$. Note that the scales of the Y axes are different.

## SILICON CARBIDE

Silicon carbide grains are classified based on their C, N and Si isotopic ratios [34]. Mainstream grains are defined as having $10 < {}^{12}C/^{13}C < 100$, mostly isotopically light N and heavy Si, and comprise ≥ 93 % of the SiC grains in meteorites [35]. Y grains are defined as having $^{12}C/^{13}C \geq 100$, isotopically light N and Si isotopic ratios that plot to the right of the mainstream correlation line in a Si three-isotope plot [36]. Z grains have C and N isotopic ratios similar to those of mainstream grains but $^{29}Si/^{28}Si$ ratios that are lower than solar and $^{30}Si/^{28}Si$ ratios that are higher than those of mainstream grains [37]. Mainstream, Y and Z grains formed in AGB stars with a range of metallicity: mainstream grains in stars with close-to-solar metallicity, Y grains in stars with half solar metallicity, and Z grains in stars with one-third of solar metallicity [38]. Altogether, they comprise about 95 % of the total SiC grains. A+B grains, showing low $^{12}C/^{13}C$ (≤ 10) and a range of $^{14}N/^{15}N$ ratios, have multiple stellar sources including J stars and born-again AGB stars [39].

X grains, comprising 1 % of SiC grains, have isotopically light C and heavy N, $^{28}Si$ excesses and high inferred $^{26}Al/^{27}Al$ ratios (~ 0.1) [40-42]. A few grains show evidence for the initial presence of $^{44}Ti$, which can only be produced during explosive nucleosynthesis, in the form of $^{44}Ca$ excesses [43]. Their isotopic signatures, similar to those of low-density graphite grains, indicate that they formed in core-collapse supernovae. C grains are also considered to have formed in supernovae [44-47]. C grains are very rare compared with other types of SiC grains and their abundances strongly depend on grain size: they are far more abundant in smaller grains. From the Presolar Grain Database [48], we calculated the abundance of C grains to be 0.077 %.

In summary, SiC grains formed in AGB stars comprise 95%, whereas those formed in supernovae comprise a mere 1 %, indicating that AGB stars are a dominant producer of SiC grains. From the abundance of SiC in the Murchison meteorite, 5.85 ppm, we calculate the abundance of SiC grains from AGB stars to be 5.6 ppm, while that of SiC grains from supernovae to be 0.063 ppm.

## GRAIN FORMATION IN SUPERNOVAE AND AGB STARS

The abundances of graphite and SiC grains from supernovae and AGB stars in the Murchison meteorite are summarized in Table 1. Graphite grains from AGB stars are about twice as abundant as those from supernovae but the abundances are not extremely different. In contrast, AGB stars are the dominant sources of SiC grains. The majority of 23 % of the graphite grains, which are not assigned to either supernovae or AGB stars, have isotopically light C. Many grains with $^{12}C/^{13}C \sim 10$, except those with supernova signatures, do not show isotopic anomalies in the other elements, thus it is difficult to probe their stellar sources. J stars and born-again AGB stars have been proposed for stellar sources of some of the grains [33, 49, 50].

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**TABLE 1.** Abundances of graphite and SiC from supernovae and AGB stars in the Murchison meteorite.

| Mineral | Supernovae | AGB stars |
|---|---|---|
| Graphite | 0.24 ppm (27 %) | 0.44 ppm (50%) |
| SiC | 0.063 ppm (1 %) | 5.6 ppm (95 %) |

Note: The percentages indicate the fractions relative to the total amount of the mineral type in the Murchison meteorite.

Next, we focus on grain formation in the two stellar sources. When we probe grain formation from the abundances of different types of minerals in meteorites, we need to consider how well the abundances of the grains reflect their original source abundances. Grains, after forming in stellar outflow, experienced several grain destruction processes [51] and different types of minerals would certainly be affected in different ways. If one type of grains is more susceptible to grain destruction than another, we need to take it into consideration. We do not have any data to compare how graphite and SiC fare in space. SiC is a hard mineral used as polishing powder, while graphite is softer. Therefore, we speculate that SiC had survived better than graphite in space. In the meteorite parent body, SiC is more resistant to metamorphism than graphite [52] and SiC has been better preserved in meteorites than graphite. Since graphite grains are more easily destroyed than SiC during the journey to earth and in meteorite parent bodies, the higher abundance of graphite from supernovae than that of SiC must mean that core-collapse supernovae produce considerably more graphite grains than SiC grains.

The abundances of SiC grains from AGB stars are more than one order of magnitude higher than that of graphite grains from AGB stars. Since SiC is likely to survive better than graphite, it is difficult to say whether or not AGB stars produced more SiC grains than graphite grains. One thing we can point out is the difference in metallicity of the parent AGB stars of graphite and SiC. Graphite grains formed in low-metallicity ($Z = 3 \times 10^{-3}$, $Z = 6 \times 10^{-3}$ for 3 $M_\odot$ only) stars and SiC grains formed in close-to-solar metallicity stars. This difference in metallicity might be one of the reasons in the difference in the abundances of graphite and SiC grains from AGB stars in the Murchison meteorite.

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