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Presolar silicon carbide grains and their parent stars

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Abstract–Carbon stars are an important source of presolar TiC, SiC, and graphite grains found in meteorites. The elemental abundances in the stellar sources of the SiC grains are inferred by using condensation calculations. These elemental abundances, together with C isotopic compositions, are used to identify possible groups of carbon stars that may have contributed SiC grains to the presolar dust cloud. The most likely parent stars of meteoritic SiC mainstream grains are N-type carbon stars and evolved subgiant CH stars. Both have s-process element abundances higher than solar and $10 < {}^{12}C/{}^{13}C < 100$ ratios. The J stars and giant CH stars, with solar and greater than solar abundances of s-process elements, respectively, are good candidate parents for the 'A' and 'B' SiC grains with low ${}^{12}C/{}^{13}C$ ratios. A special subgroup of CH giant stars with very large ${}^{12}C/{}^{13}C$ ratios could have parented the 'Y' SiC grains with ${}^{12}C/{}^{13}C$ ratios > 100. The carbon star population (*e.g.*, N, R, J, CH groups) needed to provide the observed SiC grains is compared to the current population of carbon stars. This comparison suggests that low-metallicity CH stars may have been more abundant in the past (>4.5 Ga ago) than at present. This suggestion is also supported by condensation-chemistry modeling of the trace element patterns in the SiC grains that shows that subsolar Fe abundances may be required in the stellar sources for many SiC grains. The results of this study suggest that presolar SiC grains in meteorites can provide information about carbon stars during galactic evolution.

INTRODUCTION

In the past years, much progress has been made in identifying and analyzing presolar grains in meteorites (see Anders and Zinner, 1993; Ott, 1993 for reviews). Most work has been done on graphite, diamond, and SiC grains because these grains are resistant to chemical isolation procedures. In addition, these grains are reduced whereas most meteoritic constituents are oxidized, which further aids grain identification. The characteristic isotopic and chemical compositions of graphite and SiC grains found in meteorites indicate that the grains either survived or were never subjected to significant thermal processing in the solar nebula and on meteorite parent bodies (Fegley, 1988, 1993; Fegley and Prinn, 1989; Huss, 1990). Thus, these grains are most likely remnant constituents of the presolar dust cloud from which our solar system formed. The isotopic and chemical composition of these grains, therefore, must reflect the stellar sources that contributed dust to the presolar cloud.

Among proposed stellar sources for presolar graphite and SiC grains are carbon stars, Wolf-Rayet stars, and supernovae (Anders and Zinner, 1993; Ott, 1993). Here we focus on carbon stars that seem to be a major source of the reduced presolar grains, as indicated by the similar isotopic compositions and chemical signatures of the grains and carbon stars (see also Gallino *et al.*, 1990, 1993, 1994). We previously showed that trace element patterns in SiC grains are explained by fractional condensation from carbon stars (Lodders and Fegley, 1995). The observation of the predicted complementary abundance patterns in carbon star atmospheres provides support for the fractional condensation models (Lodders and Fegley, 1997a,b).

Here we attempt to use trace element chemistry and C isotopic compositions to derive the population of carbon stars responsible for producing the observed SiC grain population. The following sections describe some physical and chemical properties of the different groups of carbon stars and give a brief summary of SiC grain properties. We then compare these properties to identify possible carbon star parents of the SiC grains found in meteorites.

CHARACTERISTICS OF CARBON STARS

Carbon stars are late-type stars with effective temperatures (T_{eff}) < 7000 K and C/O ratios equal to, or greater than, unity. In particular, C/O ≥ 1 in the coolest carbon stars (T_{eff} < 3000 K) favors production of reduced condensates (TiC, graphite, SiC) in their stellar outflows, which results in formation of the dusty circumstellar shells often observed around cool carbon stars. In some instances, the circumstellar shell becomes so thick that it almost completely obscures the central star. Such stars cannot be detected at optical wavelengths but only by infrared emission from heated dust.

The optical carbon stars are divided into several subgroups, which depends on their spectral type (T_{eff}) and chemical composition (atomic and molecular bands). The two major groups are the cooler N stars and the hotter R stars. Further subdivisions occur within these two groups. For example, stars with strong ${}^{13}C$ bands are called J stars, and stars with a strong G band due to CH are called CH stars. The major carbon star groups are the giant N, J, R, and CH stars, the subgiant CH stars, and the supergiant HdC type stars. To facilitate the description of the different carbon star groups, a list of representative stars and their properties within each group, together with the data sources, is given in the appendix. The data and data sources in the appendix are also used to produce Fig. 1a,b.

The plots in Fig. 1 are useful for grouping the different types of carbon stars according to their C isotopic ratios, effective temperatures, metallicities, and s-process elemental abundances. Figure 1a shows a plot of Fe abundances *vs.* T_{eff}, and Fig. 1b gives a plot of C isotopic composition *vs.* Fe abundance for carbon stars. The Fe abundances are plotted on the astronomical logarithmic dex scale where $[Fe/H] = \log (Fe/H)_{star} - \log (Fe/H)_{Sun}$. The carbon stars fall into distinct groups on the two plots. Data for the R CrB-type stars

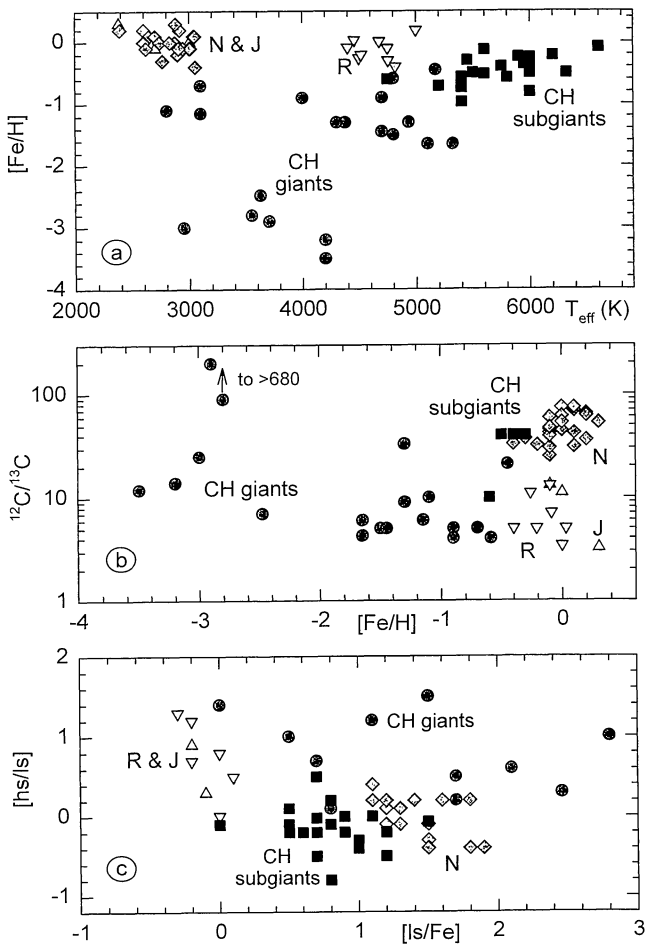

FIG. 1. Plots of Fe abundance *vs.* effective temperature and $^{12}C/^{13}C$ ratios *vs.* Fe abundance of carbon stars allow a characterization of the various carbon star groups (a and b). The bottom graph (c) shows the log of solar-normalized abundance ratios ([ls/Fe] and [hs/ls]) of light (ls) and heavy (hs) s-process elements. The notation is $[M/Fe] = \log (M/Fe)_{star} - \log(M/Fe)_{Sun}$. All these criteria are needed to group the stars. The data sources used to make these plots are listed in the appendix.

are not plotted because these stars are strongly depleted in H (see also their description below). Note that all three criteria, T_{eff}, [Fe/H], and C isotopic composition, are needed to distinguish the carbon star groups. For example, in Fig. 1a, the cool N- and J-type stars of similar metallicity plot together but are resolved in Fig. 1b by their different $^{12}C/^{13}C$ ratios. Conversely, R and J stars or N and CH subgiant stars display similar [Fe/H] and $^{12}C/^{13}C$ ratios on Fig. 1b, but R and J stars or N and CH subgiant stars are resolved by their different effective temperatures in Fig. 1a.

Other distinguishing characteristics of the different carbon star groups are the abundances of the heavier elements produced by the s-process. Following the nomenclature often used in the carbon star literature, we denote the lighter s-process elements (*e.g.*, Sr, Y, Zr) by "ls" and the heavier s-process elements (*e.g.*, Ba, La, Nd) by "hs". The hs/ls ratio can be used as a neutron exposure index (see Luck and Bond, 1982, 1991). In Fig. 1c, we plot the solar-normalized log ls/Fe (=[ls/Fe]) ratio *vs.* the solar normalized log abundance ratio hs/ls (=[hs/ls]). Abundances are not easy to determine in carbon stars, and uncertainties in the abundances are characteristically ±0.5 dex; however, abundance trends are clearly resolved even within the given uncertainties.

The J and R stars have solar [ls/Fe] ratios but their [hs/ls] ratios indicate that the heavier s-process elements can be enriched by up to a factor of ~15. The CH subgiants and N stars have ls enrichments by factors of 10 to 100× solar (relative to Fe). Their [hs/ls] ratios are solar, which shows that s-process elements are uniformly enriched. The CH giants have [ls/Fe] ratios ranging from solar to +2.8 and their [hs/ls] ratios indicate that the hs elements are often more enriched than the ls elements. In the next paragraphs, we summarize important characteristics for each carbon star group and some additional information useful for constraining SiC grain sources.

N Stars

The most abundant carbon stars are N stars. The N stars are variable stars (periodic changes in brightness, T_{eff}, and radius) and often have circumstellar envelopes in which carbon and SiC dust are seen in infrared emission. The Fe abundances in N stars are essentially solar (Lambert *et al.*, 1986). The metallicity of N stars (approximately solar) and their radial velocities (Eggen, 1972a) indicate that they are young disk stars of population I. Lambert *et al.* (1986) found effective temperatures of ~2850 K and $^{12}C/^{13}C$ ratios of 19–97 for 25 N stars. Ohnaka and Tsuji (1996) found higher effective temperatures (~3000 K) and lower $^{12}C/^{13}C$ ratios of 9–66 for ~60 N stars. For the stars common to both studies, Ohnaka and Tsuji found systematically higher T_{eff} and lower C isotopic ratios. This illustrates the difficulties in analyzing the spectra of cool carbon stars. Nevertheless, these variations do not affect significantly the stellar grouping.

The ls/Fe and hs/Fe abundance ratios in N stars are typically 10 to 100× solar (Kilston, 1975; Utsumi, 1985). Interestingly, several different elemental abundance patterns can be recognized. Abundance anomalies are typically associated with the volatile elements Sr and Ba, which indicates that the abundance patterns could be affected by fractional condensation processes (see Lodders and Fegley, 1997a,b and below).

J Stars

The J stars (sometimes called λ 6168 stars) are characterized by low $^{12}C/^{13}C$ ratios close to the CNO burning equilibrium values of 3–5 (*e.g.*, Lambert *et al.*, 1986). There are two populations of J stars: the J(N) stars, which have low T_{eff} < 3000 K similar to normal N stars, and the J(R) stars, which have low T_{eff} ~ 5000 K similiar to other R stars. In contrast to N stars, the J stars have essentially solar abundances of ls and hs (see Fig. 1c, Utsumi, 1985). The J(N) stars, like most of the normal N stars, are variable stars and are often also surrounded by dust shells. In addition to SiC emission, the cool J stars also show silicate emission that is indicative of silicate dust in their shells (*e.g.*, Little-Marenin 1986).

R Stars

The next most abundant group of carbon stars after N stars are probably R stars. The R stars are much hotter (T_{eff} ~ 4500–5000 K) than N stars. The $^{12}C/^{13}C$ ratios of <10 are comparable to those of the cooler J stars. The distinction between J(R) and R stars is somewhat arbitrary, and it may be that all typical R stars have low $^{12}C/^{13}C$ ratios. The elemental abundances in R stars are not well known, and only very few abundance determinations are available. The approximately solar ls/Fe abundances of R stars appear similar to those in J(N) stars, but hs/Fe ratios can be slightly enriched (Dominy, 1984; Utsumi, 1985, see Fig. 1c). Within uncertainties, the elemental abundances of R stars may be comparable to those of J(N) stars.

The Fe abundances in R stars (Dominy, 1984) are somewhat lower than those in N stars, which is in accordance with the suggestion from radial velocity measurements that R stars are old disk stars (Eggen, 1972b). In contrast to N stars, R stars are often nonvariable stars. Dust, as would be indicated by infrared excesses, is apparently absent in R stars (Lloyd Evans, 1986).

Among the R stars, in particular among the early (hotter) types R0–R3, we find several stars that have been classified as CH stars and HdC stars (see below). The spectral classification of late R stars (R4–R9) or early N stars (N0–N3) is sometimes difficult to make, and elemental abundance and isotopic analyses are needed to clearly define the group to which these intermediate types of stars belong. Some of the difficulties associated with sorting out R, CH, and HdC stars are also described by Lloyd Evans (1986) and McClure (1997a). According to Eggen (1972b) and McClure (1997a), the R stars are members of the low-velocity, old disk population and, unlike the CH stars, are not members of binary systems.

There may be some uncertainty in the classification of the hotter ^{13}C-rich R and CH stars (see below) because both groups have similar spectral classification and C isotopes. The larger radial velocities of CH stars are one way to distinguish them from normal R stars, but it may also take more abundance analyses to clearly resolve these two groups. Carbon star classification can become fairly complex (*e.g.*, Yamashita, 1972, 1975a), and we refer the interested reader to Kipper *et al.* (1996) or McClure (1997a), who discuss some of the problems associated with the classification of carbon stars.

Subgiant CH Stars

The subgiant CH stars are lower luminosity F–G-type stars with strong G bands from CH in their spectra. The "CH" in the group name of these stars, however, is to indicate that these stars are carbon stars with relatively high H abundances. The description "sgCH" stars is used to distinguish the subgiant CH stars from the giant CH stars. A detailed discussion of the sgCH stars is given by Luck and Bond (1982, 1991) and Smith *et al.* (1993). The sgCH stars with $T_{eff} > 5000$ K are the hottest stars included in Fig. 1. The C/O ratios in these stars are generally ≥ 1, but some of the sgCH stars have C/O ratios below unity (Luck and Bond, 1982; Smith *et al.*, 1993). Their $^{12}C/^{13}C$ ratios typically range from 20–60 (Sneden, 1983). The Fe abundances in sgCH stars are lower than that in N, J, or R stars and range from [Fe/H] ~ 0 to –1 (see Fig. 1), which indicates that sgCH stars belong to an older population (old disk, halo) of stars.

The sgCH stars, like the N stars, are often enriched in s-process elements (*e.g.*, Luck and Bond 1982, 1991; Smith *et al.*, 1993). Typically, ls/Fe ratios are up to ~10× solar, whereas hs/Fe ratios range from solar to 10× solar. Another similarity to N stars is that different types of abundance patterns can be recognized (*e.g.*, some sgCH stars have apparent overabundances of volatile Sr).

The sgCH stars are typically nonvariable stars, and McClure (1984, 1985, 1997b) found that most of the sgCH stars are found in binary systems, which is important in understanding the abundance anomalies in these stars (Luck and Bond, 1991; Smith *et al.*, 1993). The sgCH stars are not luminous enough to be in their thermally pulsing asymptotic giant branch (TP-AGB) stage; whereas, the normal N-type carbon stars are luminous enough. Once a giant star reaches the TP-AGB evolutionary stage, C and s-process elements are produced during He shell flashes and then are dredged up into the envelope. Therefore, increased C/O ratios and overabundances of s-process elements in stars that are not located on the AGB are puzzling. However, mass transfer from an evolved companion star can plausibly explain the C-rich nature of the sgCH stars, as well as the nature of other stars with increased C/O ratios and peculiar s-process abundances such as the Ba stars or CH giant stars.

This is discussed by Luck and Bond (1991) and Smith *et al.* (1993) who suggest that the more massive star in a binary system evolves to a carbon star, from which matter is transferred to the envelope of its less evolved (*e.g.*, main sequence) companion. The mass transfer in a wide, binary system possibly occurs by stellar wind and not by Roche lobe overflow (see Boffin and Jorrison, 1988; Han *et al.*, 1995). The former carbon star becomes a white dwarf and the contaminated companion star is seen as a sgCH star enriched in C and s-process elements.

Grain condensation in the outflowing stellar winds can lead to trace element fractionations (see Lodders and Fegley, 1997a,b for details). In particular, Sr and Ba may become enriched in the gas, whereas more refractory elements such as Ti, Zr, or Mo condense into SiC. Grains can also be expelled into the interstellar medium (ISM) by radiation pressure leading to dust–gas separation. If the accreting star preferentially accumulates the gas during the binary mass transfer, Sr and Ba become relatively enriched in its surface atmosphere. The C isotopic composition of the accreting star also becomes altered. Assuming that the carbon star that loses mass had a typical average $^{12}C/^{13}C$ ratio ~ 50 (Lambert *et al.*, 1986), and the main sequence star had solar $^{12}C/^{13}C$ ratio = 90, the created subgiant should have a ratio between these two values, which is consistent with a $^{12}C/^{13}C$ ratio > 40 found for sgCH stars by Sneden (1983).

Mass transfer also causes the contaminated star to move up in the main sequence (Luck and Bond, 1991). Eventually, the sgCH star, entering its mass-loss stage, ascends to the giant branch and becomes a CH giant star or a Ba star. Depending on the thickness of the accreted layer and the depth of the convective envelope at that stage of evolution, the dilution of the accreted layer by freshly dredged-up material from the interior of the star may not alter significantly the surface abundances (C/O ratio, s-process elements). In that case, grains forming in the outflow of the evolved star may acquire the abundance signatures of the former sgCH star.

CH Stars

The CH stars have been investigated by several authors (*e.g.*, Yamashita, 1975b; Hartwick and Cowley, 1985; Vanture, 1992a–c; Kipper, 1992; Kipper and Kipper, 1990; Kipper and Jorgensen 1994; Kipper *et al.*, 1996). The CH giant stars are mainly early, R-type stars but, like sgCH stars, are relatively H-rich and show relatively strong G bands of CH in their spectra. The CH stars have a wide range in T_{eff} from ~3000 to ~5500 K. One of the main characteristics of these stars is their low Fe abundance, which typically ranges from [Fe/H] = –1 to –2 (Fig. 1 and appendix). A few CH stars show even lower Fe abundances of [Fe/H] ~ –3 (*e.g.*, Kipper, 1992; Kipper *et al.*, 1996; Barbuy *et al.*, 1997), which places these stars among the most metal-poor objects known. The differences in [Fe/H] ratios among CH stars suggest the occurrence of two subgroups of CH stars. This division is also suggested from the dual groupings of $^{12}C/^{13}C$ ratios among CH stars (Tsuji *et al.*, 1991; Aoki and Tsuji, 1997). Most of the CH stars with –2 < [Fe/H] < –1 have $^{12}C/^{13}C$ ratios < 10, whereas some CH stars with [Fe/H] ratios < –2.5 have a very high $^{12}C/^{13}C$ ratio of ≥ 90 (Kipper and Kipper, 1990; Tsuji *et al.*, 1991; Kipper, 1992; Aoki and Tsuji, 1997). The low-Fe abundances and high radial velocities of CH stars suggest

that they are population II objects in the galactic halo (Eggen, 1972b). Also, CH stars occur in old globular clusters (*e.g.*, Bell and Dickins, 1974).

The Fe-normalized abundances of the α elements (*e.g.*, Al, Si, Ca) in CH giant stars with $^{12}C/^{13}C$ ratios ≤ 10 plot along the solar α/Fe ratio. The s-process elemental abundances in CH stars are generally high. The ls/Fe ratios are typically ~10 to 100× the solar ratio, whereas hs/Fe ratios range from 10 to 1000× solar, as reflected by the [hs/ls] ratios in Fig. 1c.

Elemental abundances for CH stars with very low metallicity were measured by Kipper and Kipper (1990), Kipper (1992), Kipper *et al.* (1996), and Barbuy *et al.* (1997). Unlike all other carbon stars, where [α/Fe] ratios plot within ~0.5 dex of the solar value, the [α/Fe] ratios in these stars plot between 0.8–1.5 dex. This indicates that α elements are more abundant than Fe, which is a trend similar to that observed in normal giants of low metallicity. For giants with [Fe/H] ratios < –2, the α elements are enriched 0.2–0.5 dex relative to Fe and the Sun (*e.g.*, Luck and Bond, 1981). The CH star V Ari, with [Fe/H] ratios ~ –2.8 and an unusually high $^{12}C/^{13}C$ ratio, seems to have even higher α element/Fe ratios ([α/Fe] = 1–1.5 dex) than typically observed in low-metallicity stars. Abundances of the neutron capture elements are very high in the extreme CH stars TT CVn and V Ari (Kipper and Kipper, 1990; Kipper, 1992). The ls/Fe and hs/Fe ratios in the extreme CH star V Ari plot at ~1000 to 10 000× solar, with an apparent increase of s-process elemental abundances from ls to hs (Kipper and Kipper, 1990). The extreme abundance ratios are due, in part, to the low Fe abundance in this star, [Fe/H] = –2.8, which causes an increase in the Fe-normalized abundances. The abundance data suggest that Sr is depleted relative to other ls such as Y or Zr and that Ba is depleted relative to other hs, which may indicate chemical fractionation of these two volatile elements.

An important difference between CH stars and other groups of carbon stars is the high frequency of CH stars in binary systems (McClure and Woodsworth, 1990; McClure, 1985). The binary nature of the population II CH stars is comparable to the binary Ba stars of population I. The latter also show similar s-process element enrichments but have C/O ratios somewhat below unity. As mentioned above, the peculiar abundance patterns in CH stars may have been established by contamination during mass transfer from a companion star. (In the low-metallicity stars, the absolute amount of C and O is lower and, thus, mass transfer of C-rich material is more likely to increase the C/O ratio and produce a CH star.)

However, not all CH stars are binaries. As mentioned above, the C isotopes divide the CH stars into two groups. The CH stars with very high $^{12}C/^{13}C$ ratios are apparently not binaries. Interestingly, these CH stars are also the most metal poor ([Fe/H] ratios < –2.5; see Fig. 1), whereas the CH stars with low $^{12}C/^{13}C$ ratios generally have metallicities ranging from [Fe/H] = –0.5 to –1.5. The variable, ^{12}C-rich CH stars may be regarded as population II analogs of the N carbon stars from population I.

Most of the CH stars with a low $^{12}C/^{13}C$ ratio (<10) are confirmed to be in binary systems. They are probably the evolved less-massive companion stars that previously accreted material from a carbon star (see the mass transfer discussion for the sgCH stars). Once the contaminated star evolves onto the red giant branch, it may become a CH giant star. At this stage, products from nuclear processing inside the star can be dredged up into the envelope. These dredge-up products should either decrease the $^{12}C/^{13}C$ ratio, as typically seen in red giants (by adding ^{13}C made during CNO burning), or increase the $^{12}C/^{13}C$ ratio in case the star is massive enough to enter its normal, carbon star stage and produce ^{12}C by triple alpha burning. In the latter case, additional s-process elements are also produced and mixed into the previously contaminated envelope.

The first evolutionary sequence involving dredge up of CNO burning products may apply to the binary CH stars, which mainly have $^{12}C/^{13}C$ ratios < 10. Condensation in the outflows of these stars then produces reduced grains that have enriched abundances of the s-process elements and $^{12}C/^{13}C$ ratios < 10. In the second evolutionary sequence, it is more difficult to find out whether the carbon star was previously contaminated or not because the mass transfer as well as both the interior nucleosynthetic processes and dredge-up contribute to enrichments of s-process elements and increase the $^{12}C/^{13}C$ ratios.

HdC Stars

Only ~30 of the H-deficient carbon stars are known. Reviews of these stars are given by Feast (1975) and Kilkenny (1992) from which most of the following information is taken. The HdC stars show a wide range of effective temperatures and the group includes variable and nonvariable members. Variable HdC stars are named after the prototype star R Coronae Borealis (R CrB). It is believed that the HdC stars lost their H shell and, as a consequence, the G band due to CH is almost completely absent in these stars. Hydrogen in HdC stars can be as low as 10^{-5}× the solar value. Carbon is enhanced (≥10× solar) in these supergiants and is the second most abundant element, after He, in these stars. Other elements, which include the s-process elements, seem to be close to solar in most HdC stars (*e.g.*, Warner, 1967; Cottrell and Lambert, 1982; Searle, 1961). Bands of ^{13}C are not evident in many of the HdC stars (*e.g.*, Yamashita, 1972). Infrared observations show that all R CrB stars are surrounded by dust shells, which are most likely composed of glassy or amorphous C (see Kilkenny, 1992). Thus, this type of star, although rare (because short lived?), may also have contributed dust to the presolar dust cloud. For the current discussion, we will not consider the HdC stars much further, because this relatively rare group probably did not contribute to the SiC grains in the sample studied by Amari *et al.* (1995) (see below).

CHARACTERISTICS OF PRESOLAR METEORITIC SILICON CARBIDE GRAINS

The presolar SiC grains isolated from meteorites can be grouped according to their isotopic and chemical composition. Amari *et al.* (1995) measured the C, N and Si isotopic composition and the abundances of several trace elements in SiC grains. Their work revealed that presolar SiC grains from meteorites possess a variety of different elemental abundance patterns. The CI chondrite and Si normalized, trace element abundance patterns are either flat, flat with more or less uniform s-process element enrichments, or show additional relative depletions in Ba and/or Sr. Major elements (Fe, Ca, Al) are typically depleted in the SiC grains (see Amari *et al.*, 1995, for a detailed description). Detailed studies on thousands of presolar SiC grains allowed six types of grains to be distinguished by their C, N, and Si isotopic compositions (*e.g.*, Amari *et al.*, 1995; Hoppe *et al.*, 1994, 1996, 1997). The $^{12}C/^{13}C$ ratios and designations of the six groups are as follows: (1) Mainstream Grains (MSG), which have 20 < $^{12}C/^{13}C$ < 120 ratios and are the most common grains; (2) 'A' grains, with $^{12}C/^{13}C$ ratios < 3.5; (3) 'B' grains, with 3.5 < $^{12}C/^{13}C$ < 10 ratios; (4) 'X' grains, with $^{12}C/^{13}C$ ratios > 150; (5) 'Y' grains, with 150 < $^{12}C/^{13}C$ < 260 ratios; and (6) the group of 'Z' grains, with 10 < $^{12}C/^{13}C$ <120 ratios.

The groups are also characterized by the $^{14}N/^{15}N$ ratios and Si isotopic compositions of the grains. In particular, the X, Y, and Z grains have Si isotopic compositions off the line with a slope ~1.34 defined in the three Si-isotope plot by the MSG, A and B grains (see *e.g.*, Hoppe *et al.*, 1994, 1996, 1997). The X grains most likely originated in supernovae ejecta (Amari *et al.*, 1995) and are not discussed here any further. Both the Y and Z grains are typically depleted in ^{29}Si and enriched in ^{30}Si (relative to solar); and the Z grains may be extreme Y grains in this respect, although their $^{12}C/^{13}C$ ratios are lower than that of the Y grains. Unfortunately, the Z grains have not been analyzed yet for their trace element content, which could help in understanding whether or not a relationship exists between Y and Z grains.

The C isotopic composition is the only isotopic ratio that is generally measured for carbon stars. Thus, we do not include the N or Si isotopes in our comparison of grains and stars. One of the puzzling results obtained by Amari *et al.* (1995) is that trace element abundance patterns of the SiC grains did not necessarily correlate with the C isotopic compositions of the grains. For example, grains grouped by their $^{12}C/^{13}C$ ratios as either MSG, A, or B may show similar elemental abundance patterns (see, *e.g.*, Fig. 1a,b,c,e, or h of Amari *et al.*, 1995).

GROUPING STARS AND GRAINS

The key question is how the major characteristics of carbon stars and SiC grains are related to each other. The C isotopic compositions alone are not sufficient to identify the parent stars for the SiC grains. For example, the J, R, and the majority of CH stars are ^{13}C-rich and could be parents for the A and B grains. Although N and Si isotopes are measured in the SiC grains, very few observations of N and Si isotopic compositions of carbon stars are available and their N and Si isotopic compositions are essentially unknown. Thus, at present, N and Si isotopes cannot be used to relate SiC grains to their parent stars until observations constrain the N and Si isotopic ratios for carbon stars.

On the other hand, the trace element abundances of the stars can serve as guides to identify their offspring SiC grains. As the variety of SiC grain abundance patterns shows, refractory trace elements were fractionated when they condensed into SiC grains. We use condensation calculations to deduce the composition of the source region of the SiC grains. Details of these calculations are discussed by Lodders and Fegley (1995, 1997a,b).

We have used condensation calculations in combination with observed stellar compositions to separate the SiC grains into four classes according to their s-process elemental abundances (see Table 8 of Lodders and Fegley, 1995). Within these four classes, the $^{12}C/^{13}C$ isotopic ratios further constrain the types of stars that may have contributed certain types of SiC grains. A summary and update of this classification scheme is given in Table 1, where carbon star properties are compared to SiC grain properties. The next section describes which types of grains may be linked to different types of stars.

Mainstream Grains

The range of C isotopic compositions of mainstream SiC grains coincides with that observed in the cool N-type carbon stars ($19 < {}^{12}C/^{13}C < 97$) and, to some extent, with that of subgiant CH stars ($\sim 20 < {}^{12}C/^{13}C < 60$, see also the appendix). The thermochemical modeling suggests that there are MSG with solar ls and hs abundances, MSG with ls and hs 3–5 and 10× solar abundances, and MSG with enriched, but variable, ls and hs abundances. Thus, the MSG are found in all classes listed in Table 1.

Most of the MSG are in classes II and III, which have ls and hs enrichments. The N stars are also enriched in s-process elements relative to solar which suggests that these SiC grains formed in the circumstellar shells of N stars. The $^{12}C/^{13}C$ ratios for the two MSG in class I indicate N-star origin, but the approximately solar composition of the s-process elements is incompatible with N-star origin. However, the s-process element, yttrium, seems to be enriched in these two grains, which indicates that weak s-processing may have occurred in the parent star. The alternative is that these two grains originated from CH subgiants, which have ls/Fe and hs/Fe ratios close to solar values (Fig. 1c). Grain formation may have occurred in evolved CH subgiant stars in their earlier AGB stages so that surface abundances were not yet changed (see section on sgCH stars above). There are also two MSG in class IV with $^{12}C/^{13}C$ ratios that indicate that they originate from N or subgiant CH stars. Modeling the trace element patterns of these grains showed that s-process elements in the source region of these grains were not uniformly enhanced as is expected for N stars. Thus, the observed abundance variations in sgCH stars provide a better match for the two MSG grains in class IV.

A and B Grains

The A and B grains are discussed together because both types of grains generally have $^{12}C/^{13}C$ ratios < 10. The A and B grains are found in class I, III, and IV of Table 1. Their trace element characteristics require at least two different types of parent stars. The A and B grains in class I most likely come from J(N) stars, because J(N) stars and these A and B grains both have low $^{12}C/^{13}C$ ratios of 3–5 and about solar abundances of s-process elements. Note that the R (and J(R)) stars also share these similarities, although the R stars seem to have somewhat higher hs abundances (see also the earlier description of R stars). Alexander (1993) suggested that R stars may be one source for the ^{13}C-rich grains. However, an R-star origin seems less likely because the J(N) stars are cooler (see Fig. 1),

TABLE 1. Proposed stellar sources for silicon carbide grains.*

Class	Stars		SiC Grains		
s-process element abundances	Type	$^{12}C/^{13}C$†	Type of grains	Number of grains	$^{12}C/^{13}C$†
Class I	N (or sgCH)	19–97 (20–60)	MSG	2	65–81
solar	J (and R?)	3–10	A and B	7	2.8–7.7
Class II	N	19–97	MSG	6	19–63
10× solar	CH with high ^{12}C	90 to >670	Y	3	117–258
Class III‡	N	19–97	MSG	21	26–77
3 to 5× solar	CH with low ^{12}C	3.5–10	A and B	10	3.0–9.7
Class IV	sgCH (or N)	20–60 (19–97)	MSG	2	63
above solar and variable	CH with low ^{12}C	3.5–10	A and B	2	1.9–6.3

*After Table 8 of Lodders and Fegley, 1995. The classification is based on the s-process elemental abundances, see text.
†Observed (ranges of) values. Stellar isotope data from Lambert *et al.* (1986); Ohnaka and Tsuji (1996) (J, N); Sneden (1983) (sgCH); Tsuji *et al.* (1991); Vanture (1992a); Aoki and Tsuji (1997) (CH); see also appendix. Silicon carbide grain classification and data from Amari *et al.* (1995).
‡The X grains also fit into class III. They probably originate from supernovae (see Amari *et al.*, 1995).
Abbreviations: MSG = mainstream grains.

and dust formation is more plausible in their circumstellar shells. Indeed, SiC dust is observed in J(N) stars, whereas dust is apparently very minor or absent in R stars (McClure, 1997). Another argument is that J(N) stars are variable stars (most R stars are not), and dust formation during variability minimum is also strongly favored (Lodders and Fegley, 1997a).

An origin of the A and B grains from J stars was also suggested by Gallino *et al.* (1994) and Hoppe *et al.* (1994). However, it needs to be emphasized that only the A and B grains in class I have solar s-process abundances typical for J(N) stars, so that other stellar sources with low $^{12}C/^{13}C$ ratios but increased s-process element abundances must be considered for the A and B grains in classes III and IV. Such possible sources are CH giant stars. Most CH stars have $^{12}C/^{13}C$ ratios < 10 and are enriched in elements produced by the s-process. In particular, the grains in group IV show different enrichments in light and heavy s-process elements, which is a characteristic of CH stars (Fig. 1c).

Y Grains

In our previous attempt to find possible stellar sources for the SiC grains, we suggested that the Y grains originate from N stars enriched in ^{12}C (Lodders and Fegley, 1995). The s-process element enrichments in Y grains require either N or CH stars as sources. The high $^{12}C/^{13}C$ ratios (>100) in these grains exclude the possibility that they may come from N stars that have $^{12}C/^{13}C$ ratios < 100 or CH giant stars with $^{12}C/^{13}C$ ratios < 10. However, some of the very low-metallicity CH stars have very large $^{12}C/^{13}C$ ratios (>100) (Tsuji *et al.,* 1991; Aoki and Tsuji, 1997). The large C isotopic ratios and enrichments in s-process elements suggests a link of the three Y grains (those with $^{12}C/^{13}C$ = 117, 161 and 258) to these exceptionally ^{12}C-rich CH stars, which may be low-metallicity analogs of N-type carbon stars.

Interestingly, the Y and Z grains are the only SiC grains that originate from carbon stars that have Si isotopic compositions not falling along the slope 1.34 line established by the MSG, A, and B grains (*e.g.*, Hoppe *et al.,* 1994, 1997). Instead, the Si isotopic compositions of these grains fall along lines with slopes of ~0.35 in the three Si-isotope plot. Such slopes are expected from s-processing in the He shell in low-mass AGB stars. Hoppe *et al.* (1997) discuss that this process is more effective in low-metallicity, low-mass stars and suggest that the Z grains originated in stars with [Fe/H] ~ –0.5. This explanation for the Si isotopic composition of the Y and Z grains is consistent with our conclusion that Y grains originated in the metal-poor, ^{12}C-rich CH stars.

GRAIN AND CARBON STAR STATISTICS

We now consider whether the stellar distribution derived from grains correlates with the observed relative abundance of carbon stars (see Table 2). The statistics for the carbon stars and SiC grains are based on literature data, with some additional assumptions.

The percentages of stars in the different subgroups of carbon stars were derived by using the Stephenson (1989) catalog of ~6000 carbon stars. Stephenson lists the R or N classification for ~1500 of these stars, but this information is not tabulated for the remaining 4500 carbon stars in his catalog. Stephenson (1989) also subdivides the 1500 classified stars as J, CH, or HdC stars. We also searched other catalogs for this information. The subgiant CH stars are not listed in Stephenson's catalog; therefore, we included 32 subgiant CH stars that we found described elsewhere in the literature in the statistics. The stellar statistics are probably biased because only a fraction of all known carbon stars have been assigned a spectral type. As noted above, the classification of carbon stars is often difficult due to the complexity of their spectra. In addition, there may also be a bias in the sampling because peculiar objects have the tendency to attract observers' attention. However, the general trends shown in Table 2, such as the rarity of CH stars, are probably valid despite these (unavoidable) difficulties in compiling the statistics.

It is just as difficult to define the statistical distribution of SiC presolar grains. Hoppe *et al.* (1994, 1996) grouped ~1550 analyzed SiC grains according to C, N, and Si isotopic composition. However, the trace element abundances are unknown in most of these 1550 grains. Unfortunately, as discussed above, the isotopic composition alone is insufficient for assigning the grains to their stellar sources because information about the trace element abundances in the grains is also required. For example, the A and B grains and the MSG grains analyzed by Amari *et al.* (1995) each fall into further subgroups defined by their trace element abundances (see Table 1).

However, the sample of 60 SiC grains analyzed by Amari *et al.* (1995) is not representative because these grains were preselected

TABLE 2. Distribution of silicon carbide grain groups and carbon star groups.

Characteristic carbon isotopes	s process/Fe ratios*	SiC grain type	frequency %	Potential carbon star source type	frequency (%)
$^{12}C/^{13}C < 10$	solar	A and B	2.0	J(N)	3.2
				R + J(R)	35.5
	>solar	A and B	3.5	giant CH (^{13}C-rich)	4.9
$20 < {}^{12}C/^{13}C < 100$	>solar	mainstream	84	N	51
	≥solar	mainstream	6	subgiant CH	2.0
$^{12}C/^{13}C > 100$	>solar	Y†	1.7	giant CH (^{12}C-rich)	0.2
$10 < {}^{12}C/^{13}C < 120$	not analyzed	Z†	1.5	old population type N, CH?	?
$170 < {}^{12}C/^{13}C < 2500$	>solar	X (^{28}Si excess)	1.4	No carbon star source but from supernovae	
$^{12}C/^{13}C >> 100$	solar	not yet identified	?	H-deficient (HdC)	3.3

*S process/Fe ratios inferred from condensation calculations to match the observed abundance patterns in SiC grains. Stellar data from spectroscopy.
†The Y and Z grains fall onto lines with slopes of ~0.35 in the three Si-isotope plot.
Data sources for SiC grains: Hoppe *et al.* (1994, 1996), and assumptions made in text. Data sources for carbon stars are described in text.

for analyses by their more or less unusual isotopic compositions, and as a consequence, A, B, and Y grains are presumably overabundant in their sample. Thus, we need to convolve the isotopic statistics from the large data set of Hoppe *et al.* (1994, 1996) with the trace element statistics from the smaller data set of Amari *et al.* (1995) to estimate the relative abundance of SiC grains that come from the different types of carbon stars.

We convolved the two data sets by assuming that the C isotopic ratios in Hoppe *et al.* (1994, 1996) and the trace element patterns measured by Amari *et al.* (1995) are representative of presolar SiC grains. For example, there are 19 A and B grains in the sample analyzed by Amari *et al.* (1995) (see Table 1). Of these grains, 37% come from sources with solar s-process element abundances, whereas the rest are from sources with greater than solar abundances of these elements (Lodders and Fegley, 1995). The A and B grains constitute ~5.6% of the sample of 1550 grains analyzed by Hoppe *et al.* (1994). We then calculate that $0.37 \times 5.6 = 2.1\%$ of all SiC grains are A and B grains with solar s-process abundances and that $0.63 \times 5.6 = 3.5\%$ of all SiC grains are A and B grains enriched in s-process elements. More trace element analyses of SiC grains from several meteorites are needed to see whether this approach really leads to a representative SiC grain population in meteorites. Nevertheless, we think that the available statistics are a good starting point for comparing the observed carbon star population with the carbon star population necessary to provide the SiC grains.

The most abundant carbon stars are N stars (~51%), and the corresponding percentage of MSG with enriched s-process elements (*i.e.*, MSG from N stars) is 84%. The next most abundant carbon stars are the ^{13}C-rich R stars. They do not show dusty shells and are not expected to contribute dust; thus, we did not assign grain types to them. Now we consider the less abundant carbon stars.

The sgCH stars with $20 < {}^{12}C/{}^{13}C < 100$ comprise ~2% of the stellar sample, whereas the corresponding MSG with variable s-process element abundances are 6% of all SiC grains. The J and ^{13}C-rich CH stars are good candidate sources for the A and B grains. About 2% of the grains apparently originate from cool J(N) stars, which make up ~3.2% of the carbon stars and provide a reasonable match to the grain population. The ^{13}C-rich CH stars comprise 4.9% of the carbon stars, whereas the corresponding A and B grains with enriched s-process elements are 3.5% of the SiC grains.

The percentage of Y grains is 1.7%, and their parent CH stars with large $^{12}C/^{13}C$ ratios comprise ~0.1% of carbon stars. Only two of these stars were analyzed for their isotopic and trace element compositions (see Aoki and Tsuji, 1997; Kipper and Kipper, 1990; Kipper, 1992), but more of these exotic stars may be among the metal-poor stars in the galactic halo (see also the discussion of extreme metal-poor CH stars by Barbuy *et al.*, 1997). The low-metallicity CH stars are also plausible sources for the Z grains (1.5% of all grains), but trace element data on these grains are needed to confirm this suggestion.

The statistics in Table 2 lead us to conclude that the percentage of grains that come from CH stars is higher than the percentage of CH stars in our stellar statistics. The apparent disparity could have three possible explanations: (1) the apparent percentage of CH stars in Table 2 is lower than the true percentage because some CH stars may have been incorrectly classified as R stars. However, the G band in CH stars is typically strong, which allows relatively easy identification of these stars; (2) the apparent percentage of SiC grains from CH stars is higher than the true percentage because the SiC grain samples are not representative of the SiC grain population accreted by the presolar cloud. Further trace element and isotopic analyses of SiC grains from different types of meteorites are needed to test this explanation; and (3) neither the SiC grain nor the carbon star statistics are significantly biased, and the large percentage of SiC grains derived from CH stars shows that CH stars comprised a larger percentage of all carbon stars ~4.55 Ga ago than they do today. We discuss this point later.

The HdC stars are more abundant (3.3%) than CH stars with high $^{12}C/^{13}C$ ratios, but no grains with large $^{12}C/^{13}C$ ratios and approximately solar abundances are in the SiC sample studied by Amari *et al.* (1995). The SiC grains that originate from HdC stars would show large $^{12}C/^{13}C$ ratios (>100) and possess approximately relative solar abundances of α, ls and hs elements. However, we want to point out that the HdC stars with their C-rich dust shells are attractive sources for the presolar *graphite* grains with very large $^{12}C/^{13}C$ ratios isolated from meteorites. Amari *et al.* (1993) have proposed Wolf-Rayet (WR) stars as sources for these ^{12}C-rich (and ^{18}O-rich) graphite grains. They also note that the $^{20}Ne/^{22}Ne$ isotopic ratios predicted from the massive WR stars are much higher than the observed $^{20}Ne/^{22}Ne$ ratio of ~0.0086 in the graphite grains. The lower mass HdC stars may be better suited to explain the observed $^{20}Ne/^{22}Ne$ ratios. Amari *et al.* (1993) discuss that the lower limit of the $^{20}Ne/^{22}Ne$ ratio can be obtained from the initial $^{20}Ne/\Sigma CNO$ ratio, which is ~0.087 for solar composition. In the star R CrB, the sum of CNO abundances (ΣCNO) is ~17× the solar ΣCNO (Cottrell and Lambert, 1982). Assuming a solar initial abundance for ^{20}Ne (all heavy elements are close to solar abundances in R CrB), we obtain a lower limit ratio of $^{20}Ne/^{22}Ne$ ~ 0.005 in R CrB, which is of the same magnitude as the $^{20}Ne/^{22}Ne$ ratio in the graphite grains. The derivation of these graphite grains from HdC stars is a topic that requires more investigation.

Are Present-day Carbon Stars Representative of Silicon Carbide Grain Parent Stars?

As discussed by Lodders and Fegley (1995, 1997b), trace elements Ca and Al in SiC are reasonably well matched by fractional condensation, but the match for Fe is less satisfactory. Assuming ideal solid solution, the calculated abundances of Fe are consistently higher than actually observed in the SiC grains. In some cases, the calculated Al and Ca abundances are also higher than the observed values (see Fig. 9 of Lodders and Fegley, 1995). There are three possible reasons why the calculated abundances may be higher than observed.

In the calculations, we assume ideal solubility of CaS, AlN, and Fe_3C in SiC. The solid solutions may be nonideal, but activity coefficients for AlN, CaS or Fe_3C in SiC are not known. The cubic crystal structure of SiC, CaS, AlN, and Fe_3C supports the assumption of ideal solution behavior in SiC, and the calculated and observed abundances for Ca and Al are often in good agreement (see Fig. 9 in Lodders and Fegley, 1995). Thus, the assumption of ideality appears reasonable but cannot be proven until activity coefficients are measured.

Alternatively, instead of condensing into SiC, Ca, Al, and Fe_3C may form their own condensates because the condensation temperatures of pure CaS, AlN, and Fe_3C are close to the temperatures where larger amounts of these elements can condense into SiC. However, the agreement of calculated and observed abundances of Ca and Al in many SiC grains makes it likely that solid solution formation takes place rather than the formation of pure CaS or AlN.

Another possible explanation for the apparent disparity between the (lower) observed and (higher) calculated abundances is that the

grains originated from stars with subsolar metallicities. For example, the SiC grains with trace element patterns called "enriched 3" have Si-normalized Fe abundances ranging from 5.5×10^{-3} to 1.1×10^{-4} (see Amari *et al.*, 1995). If we assume that Fe_3C dissolves ideally into SiC, we would expect normalized Fe abundances ranging from ~0.4 to ~0.05. Thus, observed Fe abundances are ~70 to 430× lower than expected if solar Fe abundances are used in the calculations. The observations of current-day N stars indicate that they have about solar abundances of Ca and Fe (Lambert *et al.*, 1986), but the parent stars of the presolar SiC grains may have had lower metallicities more than 4.5 Ga ago.

The galactic halo is a window back in time, where low-metallicity carbon stars are found. As we have seen before, the ^{12}C-rich CH stars have low-Fe abundances that can be ~630× lower than the solar Fe/H value (see also Fig. 1). All heavy elements in low-metallicity stars are depleted relative to solar values, and their relative abundances (*e.g.*, the Ca/Fe ratio) remain solar until low-Fe abundances of [Fe/H] < –1 are reached. As discussed earlier, stars with [Fe/H] < –1 typically have higher α element/Fe ratios of [α/Fe] ~ 0.2–0.5 (*e.g.*, Luck and Bond, 1981) than the Sun ([α/Fe] = 0). An apparent underabundance of Fe relative to Ca is also needed to obtain an agreement between the observed and calculated abundances for Fe in the SiC grains. The derived [Ca/Fe] ~ 1.8 to 2.6 for the stellar sources of the grains is much higher than typically observed for normal low-metallicity stars. It is clear that activity coefficients are needed to refine the calculations and to see if high Ca/Fe ratios inferred from the grains are, indeed, that high. However, we think that there is an indication that the grains probably formed from carbon stars with lower metallicity. The relative trace abundance patterns of the heavier s-process elements are not affected by changes in overall metallicity as long as relative solar abundance ratios are maintained.

Our answer to the question "Are present day carbon stars representative of SiC grain parent stars?" is "not entirely." This is because of the higher fraction of CH stars needed to account for the corresponding SiC grains and the apparent need for subsolar-metallicity carbon stars to explain the low-Fe abundances in most of the SiC grains. The conclusion that CH stars were an important population in the early metal-poor era of our galaxy is supported by studies from Hartwick and Cowley (1985), who found that the local space density of the CH stars is unusually high when compared to other metal-poor giants in the galactic halo. Another important observation is that carbon stars are apparently more abundant in metal-poor local group galaxies such as the large and small Magellanic clouds, and that the carbon star abundance is inversely correlated with the [Fe/H] abundance ratio (*e.g.*, Richter and Westerlund, 1983). Thus, if the low Fe abundance in the presolar MSG SiC grains is indeed reflecting low-Fe abundances in the source stars, there may have been low-metallicity population II N star equivalents feeding dust to the presolar cloud more than 4.5 Ga ago.

SUMMARY

We refined our earlier identification of possible carbon star sources for a sample of presolar SiC grains isolated from the Murchison meteorite by Amari *et al.* (1995). The inferred stellar abundances and the C isotopic compositions of the SiC grains are compared to different groups of carbon stars. The comparison suggests that 84% of the SiC grains originated from N stars, 2% from J stars, 3.5% from normal ^{13}C-rich CH giant stars, 1.7% from ^{12}C-rich CH giants, and 6% from subgiant CH stars. No SiC grains were found to originate from HdC stars.

A comparison of the population of carbon stars supplying SiC grains to the current distribution of carbon stars suggests that the low-metallicity CH stars were apparently more abundant in the earlier era of the galaxy, which is in line with age-metallicity trends and the high density of CH stars in the galactic halo (Hartwick and Cowley, 1985). It is of great interest to obtain trace element and isotopic measurements for a larger SiC grain sample and also for presolar SiC grains from other meteorites to improve on the statistics for the stellar SiC grain sources, because this is a unique opportunity to learn about the groups of carbon stars present more than 4.5 Ga ago.

Condensation modeling of the Fe abundance in the SiC grains also suggests that their parent stars may have had subsolar metallicities and higher α element/Fe ratios, which are closer to those observed in the older population CH giant stars than are currently observed in young N or J stars. However, activity coefficient data for CaS, AlN, and Fe_3C solid solutions in SiC are needed to improve the thermochemical modeling so that the metallicities of the stellar sources of the SiC grains can be derived with better confidence. This, in turn, would give the possibility to study more aspects of galactic evolution that were recorded by the presolar grains.

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APPENDIX

The appendix appears on the following page.

TABLE A1. Properties of some stars in different carbon star groups.

Star name	Spectral type*	T_{eff} (K)	[Fe/H]	C/O	$^{12}C/^{13}C$	[ls/Fe]	[hs/ls]	V_{rad} km/s	Notes	References
N Stars										
V Aql	N6 C6,3	2700 ± 100	0.1	2.9, 1.25	74 ± 8	1.5	–0.1	37	var, YD	1,2,3,4
ST Cam	N5 C6,4	2940 ± 140	–0.1	1.14	45 ± 16	1.5	–0.3	–12	var, YD	2,3,4
X Cnc	N3 C5,4	2765 ± 145	–0.3	1.14	37 ± 15	1.6	0.2	–1	var, YD	2,3,4
U Hya	N2 C7,3	2950 ± 130	–0.1	1.14 ± 0.1	21 ± 10	1.3	0.1	–25	var, YD	1,2,3,4
W Ori	N5 C5,3	2830 ± 150	0.0	1.16	53 ± 27	1.1	0.2	16.9	var, OD	2,3,4
BL Ori	N0 C6,3	3070 ± 110	–0.1	1.04	42 ± 16	1.2	0.2	13	var, OD	2,3,4
Z Psc	N0 C7,3	3000 ± 140	–0.1	1.01	39 ± 16	1.8	0.2	18	var, YD	2,3,4
TX Psc	N0 C6,2	3055 ± 25	–0.4	1.06 ± 0.03	28 ± 13	1.3	–0.1	–11	var, YD	1,2,3,4
S Sct	N3 C5,4	3000 ± 120	–0.1	1.07	30 ± 15	1.9	–0.4	0	var, YD	2,3,4
Y Tau	N2 C7,3	2825 ± 55	0.0	1.04	49 ± 9	1.1	0.4	17	var, OD?	2,3,4
VY UMa	N0 C6,3	3050 ± 190	0.1	1.06	31 ± 14	1.5	–0.4	–5	var, YD	2,3,4
J Stars										
WZ Cas	N1p C9,1 J	3005 ± 155	0.0	1.01	4 ± 0.5	–0.1	0.3	–34.0	var, YD	2,3,4
Y CVn	N3 C5,4 J	2730	0.0†	1.95, 1.09	3.5	–0.2	0.9	11.7	var, YD	1,2,3
R Stars										
HD113801	K5p-R C2,1	4700	–0.26	1.0	15	~0	0.01	–16	OD	5
BD+33°2399	R2 C3,3	4460	+0.03	2.1	5	~0	0.08	–30	OD	5
HD156074	R0 C3,1	4980 ± 210	–0.10	2.0	8	~0	0.34	–16	nonvar, OD	5
HD168227	R5 C4,5.5 J	ND	ND	ND	ND	0.0	1.0	–19	var, YD	3
CH Subgiant Stars										
HD4395	sgCH	5500 ± 50	–0.34 ± 0.04	1.6	>40	0.5	–0.1	–0.4	bin	6,7,8,9
HD88446	sgCH	6000	–0.39 ± 0.01	1.1	ND	0.9	–0.2	62.1	bin	6,7,9
HD89948	sgCH	6000	–0.29 ± 0.2	1.6	>40	1.2	–0.5	19.2	bin	6,7,8,9
HD182274	F6V sgCH	6000	–0.43 ± 0.04	>1.2	ND	1.0	–0.4	–12.8	bin	6,7,9
HD216219	G0 II sgCH	5500 ± 100	–0.47 ± 0.08	>1.2	>40	1.0	–0.3	–8.5	bin	6,8,9,10
CH Giant Stars with low $^{12}C/^{13}C$ ratios										
HD26	C0,0 CH	5025 ± 220	–0.45 ± 0.05	1.1	10, ≥21	0.7	0.7	–213	H, bin	6,11,12,13,19
HD5223	R C1,2 CH	4340 ± 200	–1.30	ND	9 ± 2	ND	ND	–232	H	11,12,14
NQ Gem	R8 C6,2 CH	3200 ± 200	–0.70	1.21	7 ± 2	1.5	1.5	48.5	H, var, bin	3,4,15
HD187216	R3 C3,3 CH	3750 ± 250	–2.48	2.1	8 ± 2	1.5	1.5	–129	H, not bin?	13,16
HD189711	R8 C4,3 CH	3050 ± 50	–1.15	1.26	7 ± 2	1.1	1.2	–168	H, bin?	1,11,15
HD198269	R0 C1,0 CH	4650 ± 150	–1.3	2.0	6 ± 1	0.5	1.0	–207	H	12,13
HD209621	R3 C1,2 CH	4500 ± 200	–0.9	1.2	3.5, 10	0.0	1.4	–381	var, bin	11,12
CH Giant Stars with high $^{12}C/^{13}C$ ratios										
V Ari	Rp4 C4,4 CH	3550 ± 50	–2.8	1.07	90, ≥680	~2.8	~1	–176	H, var	11,13,17
TT CVn	Rp6 C3,5 CH	3710 ± 20	–2.9	ND	90, ≥500	ND	ND	–135	H, var	11,13,15,18

*Spectral type (R/N and C classification) from Yamashita (1972, 1975).
†Uncertain value.
Abbreviations: V_{rad} = heliocentric radial velocity (Eggen, 1972a,b; Yamashita, 1972, 1975a,b); [ls/Fe] = log abundance ratio of light s-process elements (Y, Zr) over Fe relative to solar; [hs/ls] = log abundance ratio of heavy, s-process rare earth elements (REE) over light, s-process elements relative to solar; var = variable star; nonvar = nonvariable star; bin = star in binary system (McClure, 1984, 1997; McClure and Woodsworth, 1990); OD = old disk; YD = young disk; H = halo; and ND = no data.
References: (1) Kilston (1975); (2) Lambert *et al.* (1986); (3) Utsumi (1985); (4) Ohnaka and Tsuji (1996); (5) Dominy (1984); (6) Luck and Bond (1982); (7) Luck and Bond (1991); (8) Sneden (1983); (9) Smith and Lambert (1986); (10) Krishnaswamy and Sneden (1985); (11) Tsuji *et al.* (1991); (12) Vanture (1992a); (13) Aoki and Tsuji (1997); (14) Bell and Dickens (1974); (15) Kipper *et al.* (1986); (16) Kipper and Jorgensen (1994); (17) Kipper and Kipper (1990); (18) Kipper (1992); and (19) Wallerstein and Greenstein (1964).