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ARE PRESOLAR SILICON CARBIDE GRAINS FROM NOVAE ACTUALLY FROM SUPERNOVAE?

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ABSTRACT

We report Si, C, N, Mg-Al, Ca, and Ti isotopic data for three micron-sized presolar SiC grains from the Murchison meteorite. These grains have very low $^{12}C/^{13}C$ and $^{14}N/^{15}N$ ratios, similar to grains for which an origin in classical ONe novae has been previously ascribed. Isotopic signatures in one grain (^{28}Si, ^{49}Ti, and ^{44}Ca excesses and a very high inferred $^{26}Al/^{27}Al$ ratio) indicate that it in fact formed in a supernova, not a nova. Similarly, a large ^{47}Ti excess in another grain argues against a nova origin. The new data raise the question whether all grains previously attributed to novae might have in fact originated in Type II supernovae. The results also point to coupled synthesis of ^{13}C and ^{15}N in Type II supernovae.

Subject headings: dust, extinction — meteors, meteoroids — novae, cataclysmic variables — nuclear reactions, nucleosynthesis, abundances — supernovae: general

1. INTRODUCTION

Chondritic meteorites contain preserved dust grains that formed in stellar winds and outflows and became part of the inventory of materials from which the solar system formed (Zinner 1998; Clayton & Nittler 2004). These *presolar* grains are identified by unusual isotopic compositions and provide astrophysical information that is complementary to that obtained from astronomical observations. In particular, since the isotopic compositions of the grains reflect those of the stellar gases from which they condensed, they can provide detailed information about stellar nucleosynthesis and mixing on a microscopic scale.

The best-studied presolar phase, silicon carbide (SiC), exhibits a broad range of isotopic compositions for a large number of elements. The isotopic data fall into a number of families or groups, which are associated with different types of stellar sources. For example, over 90% of SiC grains (the "mainstream" population) are well established to have formed in the winds of roughly solar-metallicity asymptotic giant branch (AGB) stars (Hoppe & Ott 1997; Lugaro et al. 1999, 2003). About 1% of presolar SiC grains ("X" grains) have isotopic compositions pointing to an origin in core-collapse supernovae, especially ^{44}Ca excesses from decay of short-lived ^{44}Ti and large overabundances of ^{28}Si (Nittler et al. 1996; Hoppe et al. 2000; Besmehn & Hoppe 2003). Additional populations have been associated with unusual carbon stars ("A" and "B" grains; Amari et al. 2001c) and low-metallicity AGB stars ("Y" and "Z" grains; Amari et al. 2001b; Hoppe et al. 1997).

A very small fraction (<1%) of presolar SiC grains (and a few presolar graphite grains) have been proposed to have formed in the ejecta of classical novae (Amari et al. 2001a, hereafter A01). These grains are characterized by low $^{12}C/^{13}C$ and $^{14}N/^{15}N$ ratios, relative to terrestrial values and other presolar grains, $^{30}Si/^{28}Si$ ratios higher than terrestrial, and $^{29}Si/^{28}Si$ ratios close to or lower than terrestrial. Moreover, two grains show high $^{26}Al/^{27}Al$ ratios (inferred from very large ^{26}Mg excesses accompanied by solar $^{25}Mg/^{24}Mg$ ratios). These isotopic signatures are qualitatively consistent with models of nucleosynthesis in ONe novae, thermonuclear runaways that occur on O- and Ne-rich white dwarfs in close binary systems (see, e.g., Gehrz et al. 1998 and references therein; José & Hernanz 1998). However, A01 pointed out a number of problems with assigning a nova origin to these unusual grains. First, the observed isotopic signatures in the grains are much less extreme than those of pure nova ejecta, so mixing with more than 10 times as much material with close-to-solar abundances is necessary. Second, ONe novae produce much less dust than do CO novae (Gehrz et al. 1998), yet the isotopic data point to ONe nova sources. Third, ONe nova ejecta has $O > C$, but it is usually expected that carbonaceous phases such as graphite and SiC do not form unless $C > O$, because of the high stability of the CO molecule (Lodders & Fegley 1995). In fact, recent equilibrium condensation calculations of model nova ejecta indicate that graphite and SiC can indeed form in ONe ejecta (José et al. 2004), and thus the third problem is apparently alleviated, but this still leaves the first two difficulties. In any case, resolving the origin of the ^{13}C- and ^{15}N-rich grains requires isotopic data on a larger number of grains. For example, A01 predicted that nova grains should have highly anomalous S isotopic compositions but Ti signatures similar to mainstream SiC grains from AGB stars. We report here C, N, Si, Al-Mg, Ca, and Ti isotopic data for three new ^{13}C- and ^{15}N-enriched presolar SiC grains. These data raise the possibility that this unusual class of presolar grains formed in supernova ejecta, rather than in classical novae, with implications for nucleosynthesis in supernovae.

2. EXPERIMENTAL METHODS AND RESULTS

SiC grains (<5 μm) from a Murchison residue prepared using the standard methods (Besmehn & Hoppe 2003) were deposited on a gold foil and automatically analyzed for their Si and C isotopic ratios with a Cameca IMS 6f ion microprobe (Nittler & Alexander 2003). Of 1300 measured Si-rich grains, 1150 had Si/C ratios consistent with SiC and reasonably small error bars. Of these, two grains—151-4 and 347-4—exhibited low $^{12}C/^{13}C$ ratios and high $^{30}Si/^{28}Si$ ratios consistent with previous nova grains (A01). One grain, 334-2, showed a ^{28}Si-rich composition similar to the supernova-derived X-grains (Nittler et al. 1996; Hoppe et al. 2000) but $^{12}C/^{13}C = 6.5$, similar to nova grains. These three ^{13}C-rich grains were subsequently manually

TABLE 1
Isotopic Ratios of Putative Nova Grains

Sample	$^{12}C/^{13}C$	$^{14}N/^{15}N$	$\delta^{29}Si/^{28}Si$ (‰)	$\delta^{30}Si/^{28}Si$ (‰)	$^{26}Al/^{27}Al$	$\delta^{46}Ti/^{48}Ti$ (‰)	$\delta^{47}Ti/^{48}Ti$ (‰)	$\delta^{49}Ti/^{48}Ti$ (‰)	$\delta^{50}Ti/^{48}Ti$ (‰)
M11-151-4	4.02 ± 0.07	11.6 ± 0.1	−438 ± 9	510 ± 18	0.27 ± 0.05	28 ± 59	215 ± 57	82 ± 55	−100 ± 123
M11-334-2	6.48 ± 0.08	15.8 ± 0.2	−489 ± 9	−491 ± 18	0.39 ± 0.06	−61 ± 33	−5 ± 36	380 ± 47	−20 ± 59
M11-347-4	5.59 ± 0.13	6.8 ± 0.2	−166 ± 12	927 ± 30	[a]	[a]	[a]	[a]	[a]
Terrestrial	89	272	0	0	0	0	0	0	0
X-grains[b]	13 to 7000	13 to 250	−750 to 120	−770 to 0	0.01 to 0.6	17 ± 170	17 ± 116	492 ± 236	−26 ± 44
Nova models[c]	0.3 to 3	0.1 to 10	−800 to 1800	−800 to 15000	0.07 to 0.7	0	0	0	0

Note.—Errors are 1 σ; $\delta R = (R_{meas}/R_{standard} - 1) \times 10^3$.
[a] Not measured.
[b] Nittler et al. (1996); Hoppe et al. (2000); Hoppe & Besmehn (2002); Nittler & Alexander (2003). Data are ranges, except for Ti ratios, which are weighted mean plus or minus the standard deviation of data from Hoppe & Besmehn (2002).
[c] José & Hernanz (1998); José et al. (2004).

analyzed for N isotopes using standard techniques (Zinner et al. 1989) with the IMS 6f. These measurements revealed low $^{14}N/^{15}N$ ratios similar to the previous nova grain candidates.

One of the new grains was unfortunately lost in a laboratory mishap, but two grains (334-2 and 151-4) were further analyzed for their Mg, Ti, and Ca isotopic compositions using a Cameca NanoSIMS 50 ion microprobe. The three Mg isotopes were measured together with ^{27}Al and ^{28}Si in multidetection mode. The Al^+/Mg^+ sensitivity factor (1.50 ± 0.25) required for the calculation of $^{26}Al/^{27}Al$ ratios was determined from measurements on Murchison spinel grains. Both analyzed grains exhibit huge enrichments in ^{26}Mg of over 5000 times compared with the solar isotopic abundances. The Ti isotopes were measured together with ^{28}Si and ^{52}Cr in a combined mutidetection/peak-jumping mode. Cr was included to estimate the contribution of ^{50}Cr to ^{50}Ti (which cannot be separated). Chromium-50 was calculated to make up 48% and 75% of the ion signal at mass 50 for grains 334-2 and 151-4, respectively. For the Ca isotopic analysis of grain 334-2, ^{28}Si, ^{40}Ca, ^{42}Ca, ^{44}Ca, and ^{48}Ti were measured in multidetection mode. The Ti^+/Ca^+ sensitivity factor (0.51) required for the calculation of $^{44}Ti/^{48}Ti$ ratios was taken from Besmehn & Hoppe (2003).

Isotopic data for the three grains are shown in Table 1 and Figures 1–3. The $^{12}C/^{13}C$ and $^{14}N/^{15}N$ ratios are closely similar to those previously observed (Fig. 1), but the Si isotopes differ somewhat (Fig. 2). Grains 347-4 and 151-4 are highly enriched in ^{30}Si, as observed in previous nova grains, but are somewhat more depleted in ^{29}Si than the prior data. Grain 334-2 is enriched in ^{28}Si, indistinguishable from the X-grains. The two grains analyzed for Mg and Ti isotopes both have highly enriched ^{26}Mg, with inferred $^{26}Al/^{27}Al$ ratios of 0.3–0.4 (Fig. 3) and unusual Ti isotopic compositions. Grain 151-4 has a large (21%) ^{47}Ti excess, and grain 334-2 has a large (38%) ^{49}Ti excess. Because of its isotopic similarity to X-grains, 334-2 was also subjected to a Ca isotopic measurement, which revealed a normal $^{42}Ca/^{40}Ca$ ratio ($\delta^{42}Ca = -70‰ \pm 200‰$) and a 50% excess in ^{44}Ca ($\delta^{44}Ca = 535‰ \pm 150‰$).

3. DISCUSSION

Novae are thermonuclear runaways that occur when H-rich matter accretes onto a white dwarf (WD) star from a close stellar companion. The high-temperature [(2–3) × 10^8 K] nu-

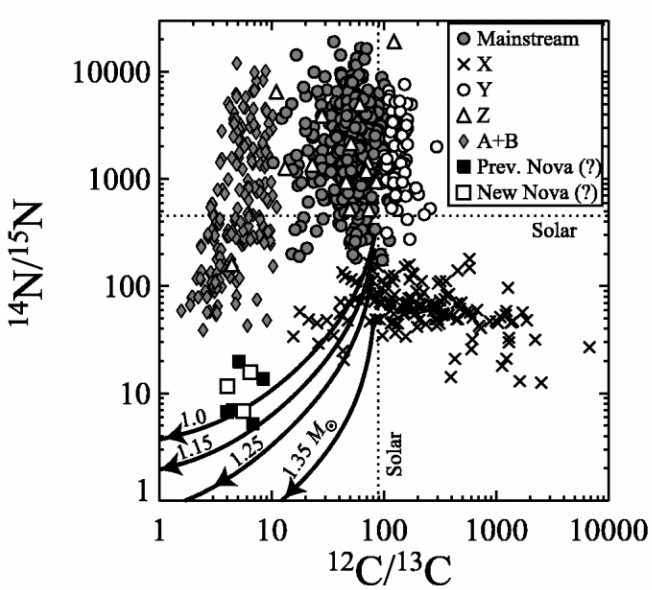

Fig. 1.—C and N isotopic ratios measured in presolar SiC grains. Data are divided into different groups, associated with different types of stellar sources. Whereas mainstream grains formed in AGB stars and X-grains in supernovae, grains with low $^{12}C/^{13}C$ and $^{14}N/^{15}N$ ratios have been attributed to classical ONe novae. Dotted lines indicate the solar composition in this and subsequent figures. The solar N isotopic ratio is taken to be that of Jupiter (Owen et al. 2001). Solid curves are mixing lines between mass-weighted ejecta of ONe novae (José et al. 2004) and the solar composition; white dwarf masses are indicated. See Zinner (1998) and Clayton & Nittler (2004) for data sources.

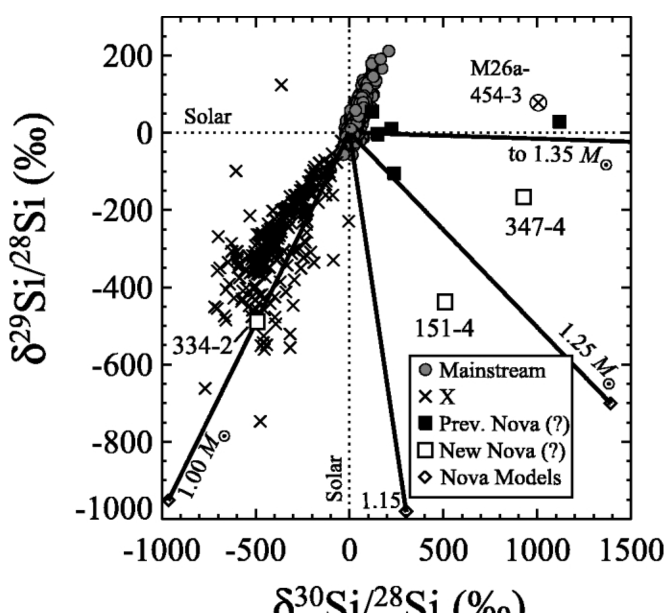

Fig. 2.—Same as Fig. 1, but for Si isotopic ratios. Ratios are expressed as δ-values, permil deviations from a terrestrial isotope standard (see Table 1 for definition). For clarity, the A, B, Y, and Z subgroups are not plotted, but the unusual grain M26a-454-3 (Nittler & Alexander 2003) is indicated.

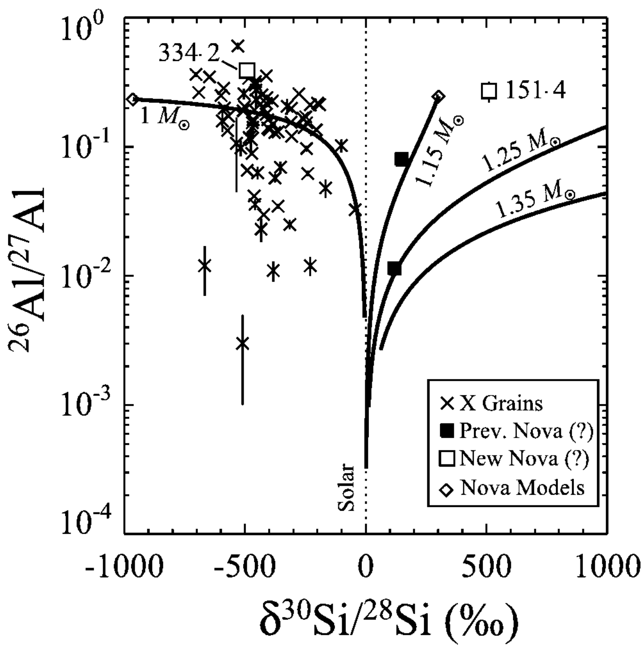

FIG. 3.—Inferred $^{26}Al/^{27}Al$ ratios plotted vs. $\delta^{30}Si$ values for SiC nova grain candidates and X-grains (see Table 1 for definition of δ-values). Solid curves are mixing lines between mass-weighted ejecta of ONe novae (José et al. 2004) and the solar composition; white dwarf masses are indicated. Grain 334-2 has higher $^{26}Al/^{27}Al$ than can be explained by the 1 $M_\odot$ ONe nova model that reproduces its Si isotopic composition (Fig. 2), whereas the other nova candidates can be explained by the models.

clear processing that follows (primarily proton capture) leads to very low $^{12}C/^{13}C$ ratios (<2), as well as significant modifications of the isotopic compositions of other light elements (perhaps up to Ca) and the synthesis of some important radioactivities, including ^{26}Al (see, e.g., Gehrz et al. 1998; José & Hernanz 1998; José et al. 2004). The precise nucleosynthesis that occurs in a nova depends on the nature of the progenitor WD, namely, whether it is composed of C and O (CO novae) or of O and Ne (ONe novae). ONe novae occur on more massive WDs ($M \gtrsim 1\ M_\odot$) than do CO novae, but the exact minimum mass for an ONe nova is unknown. A01 showed that only ONe nova models could reproduce the isotopic signatures of their putative nova grains. Shown in Figures 1 and 2 are mixing lines between the predicted compositions of ONe nova ejecta of different WD masses (José & Hernanz 1998; José et al. 2004) and the solar composition. The C, N, and Si compositions of the new grains can be qualitatively explained by the nova models at least as well as the previous grains could. Like the previous grains, the ^{30}Si enrichments in grains 151-4 and 347-4 seemingly require an origin in relatively massive novae ($M \gtrsim 1.25\ M_\odot$). In contrast, the ^{28}Si-rich composition of grain 334-2 requires that it have formed in a less massive nova. However, it still apparently requires an ONe parent, since CO nova models do not predict large ^{30}Si depletions (José & Hernanz 1998; José et al. 2004).

The consistency between observation and theory starts to break down when we consider additional isotopic systems, however. Let us first consider grain 334-2. The similarity of its Si isotopic signature to the SiC X-grains extends to its Al, Ca, and Ti composition. Its inferred $^{26}Al/^{27}Al$ ratio of 0.4 is similar to those of X-grains and considerably higher than can be explained by mixing between model 1 $M_\odot$ ONe nova ejecta and the solar composition (Fig. 3). Similarly, its Ti isotopic pattern (large ^{49}Ti enrichment and close-to-solar ratios for other Ti isotopes) is closely similar to typical X-grains (Table 1). Finally, the observed ^{44}Ca enrichment in this grain strongly points toward the initial presence of ^{44}Ti in this grain, with an inferred initial $^{44}Ti/^{48}Ti$ ratio of 0.0023 ± 0.0006. Because of the short half-life (60 yr) of ^{44}Ti and the fact that this isotope is only synthesized in supernovae, this latter isotopic signature has been used as proof of a supernova origin for X-grains (Nittler et al. 1996). Thus, grain 334-2 must also have formed in a supernova and should be classified as an X-grain. Its $^{12}C/^{13}C$ ratio is a factor of 2 lower than the lowest previous X-grain ratio, indicating that at least some supernovae have regions with both low $^{12}C/^{13}C$ and low $^{14}N/^{15}N$ ratios, in contrast to current supernova nucleosynthesis calculations (e.g., Rauscher et al. 2002). Further implications of this are discussed below.

In contrast to that of 334-2, the $^{26}Al/^{27}Al$ ratio of grain 151-4 is basically consistent with mixing between ejecta of a ~1.2 $M_\odot$ ONe nova and the solar composition (Fig. 3), though it is similar to typical X-grains as well. Its ^{47}Ti-enriched Ti isotopic composition is highly unusual, however. The nuclear processing in nova ejecta is not expected to reach high enough temperatures to affect Ti isotopes (José & Hernanz 1998; José et al. 2004), and thus the Ti isotopic composition of nova grains should reflect that of the companion star that is accreting matter onto the WD. The Ti isotopic compositions of mainstream SiC grains (from AGB stars) are best explained by a combination of Galactic chemical evolution, which determines the initial composition of the parent star, and mixing of *s*-process material into the envelope during the AGB phase (Lugaro et al. 1999; Alexander & Nittler 1999). Grain 151-4 falls far from the mainstream grains on a plot of $^{46}Ti/^{48}Ti$ versus $^{47}Ti/^{48}Ti$ ratios. Since these ratios are least affected by mixing of *s*-processed material and thus mostly represent the initial compositions of the mainstream grain parent stars, the distinct composition of 151-4 suggests that its large ^{47}Ti excess is due to nucleosynthetic effects in its parent star, not to an initial composition.

The ^{47}Ti excess of grain 151-4 thus seems to argue against a nova origin for this grain, since novae are not expected to synthesize this isotope. However, the nucleosynthetic origin of ^{47}Ti is not understood. The Galactic chemical evolution model of Timmes et al. (1995) underproduces this isotope by a factor of 5, indicating either that it is produced in sources not included in their model or that the nucleosynthetic yields used by these authors are incorrect for this isotope. A large (50%) ^{47}Ti enrichment was observed previously in a presolar graphite grain with other isotopic signatures indicating a Type II supernovae origin (Amari & Zinner 1997). This result suggests that more ^{47}Ti is produced in Type II supernovae than is predicted by current calculations and supports a supernova origin for SiC grain 151-4 as well. We note that unusual Type Ia supernovae may be a significant source of both ^{47}Ti and ^{48}Ti (Woosley & Weaver 1994), perhaps suggesting an origin for 151-4 in the ejecta of such an event. However, it is not clear that these supernovae could produce the essentially monoisotopic Ti anomaly observed in this grain.

The preceding discussion shows that at least one (334-2) and probably at least two (334-2 and 151-4; the third grain was lost before it could be analyzed for Mg, Ca, or Ti isotopes) presolar grains with low $^{12}C/^{13}C$ and $^{14}N/^{15}N$ ratios formed in supernovae, but in the past this isotopic signature has been among the most diagnostic in linking presolar grains to novae (A01). Thus, the present results raise the question whether all such grains formed in supernovae. A supernova origin for all the grains could alleviate the major problems with a nova origin, namely, the strong dilution of the nucleosynthetic signatures and the observational fact that ONe novae do not produce significant quantities of dust. However, a supernova origin raises important questions itself, not least of which is whether the isotopic signatures of the grains can be quantitatively reproduced by mixing of different supernova regions. The Si isotopic signature of the putative nova grains (^{30}Si enrichments and closer to solar or subsolar ^{29}Si) has been considered diagnostic of ONe novae (A01; José & Hernanz 1998). However, nucleosynthetic models do predict some supernova regions to have enrichments in both ^{29}Si and ^{30}Si, with larger effects in ^{30}Si (Woosley & Weaver 1995; Travaglio et al. 1999). Moreover, Nittler & Alexander (2003) reported a SiC grain, M26a-454-3 (Fig. 2), with a large ^{30}Si enrichment similar to the most extreme nova grain candidate of A01, but with $^{12}C/^{13}C = 118$, inconsistent with a nova origin. A supernova origin is considered most likely for this grain. No single supernova zone is predicted to have ^{30}Si enrichments and ^{29}Si depletions as observed in some of the proposed nova grains (Woosley & Weaver 1995; Rauscher et al. 2002). However, mixtures of the ^{28}Si-rich Si/S zone and the ^{28}Si-poor O/Si zone can reproduce such compositions, so a nova origin is not apparently required to explain this signature either. If the ^{47}Ti enrichment of grain 151-4 indeed indicates a supernova origin, then this also indicates that some supernovae can produce such a Si signature. In any case, it is clear at this point that the origin of most of the ^{13}C- and ^{15}N-rich SiC grains is ambiguous without isotopic data for additional minor elements; both nova and supernova sources should be considered viable. Further progress will require both new data and additional nova and supernova nucleosynthesis models. As discussed by A01, S might be a particularly diagnostic element, but it is not yet clear whether presolar SiC grains retain any S from their stellar sources.

The nucleosynthetic origin of ^{15}N is not well understood. It is produced in supernovae by neutrino spallation on ^{16}O, but the models of Woosley & Weaver (1995) indicate that this process does not produce sufficient amounts to explain the solar abundance. Thus, novae and AGB stars are also commonly considered as potential sources of this isotope. However, the observation of low $^{14}N/^{15}N$ ratios in the Large Magellanic Cloud and a starburst galaxy (Chin et al. 1999) indicates much stronger production in Type II supernovae than predicted by Woosley & Weaver (1995). The SiC X-grain data support this as well, since they have lower $^{14}N/^{15}N$ ratios than can be readily explained by the supernova mixing models (e.g., Hoppe et al. 2000). One possible mechanism was suggested by Langer et al. (1998), who found that including stellar rotation greatly increased the production of ^{15}N during He burning in presupernova massive stars. Moreover, these authors found that in some cases rotation-induced mixing produced a ^{13}C-rich layer just below the H-burning shell. This model provides a plausible explanation for the X-grain C and N data, including grain 334-2 reported here. The relatively uniformly ^{15}N-rich (a factor of 15 range in $^{14}N/^{15}N$ for most grains) composition of X-grains reflects a relatively uniform composition in the He-burning shells of the parent supernovae, arising from rotation-induced mixing. A variable presence and mixing of a ^{13}C layer at the top of the ^{12}C-rich He shell could then lead to the large (factor of 1000) observed range of $^{12}C/^{13}C$ ratios in the grains. A larger grid of nucleosynthesis calculations for rotating massive stars is needed in order to test this idea and see whether it can quantitatively account for the grain data and the extragalactic ^{15}N observations (Chin et al. 1999).

On a final note, previous studies of presolar O-rich grains have ruled out novae as stellar sources (e.g., Nittler 1997), since no grains have the very high $^{17}O/^{16}O$ and $^{18}O/^{16}O$ ratios that were predicted for nova ejecta (e.g., Politano et al. 1995). However, more recent calculations indicate a wider range of $^{18}O/^{16}O$ ratios compared with the previous models, and this issue should thus be revisited. For example, the highly ^{17}O-rich and slightly ^{18}O-depleted Al_2O_3 grain T54 (Nittler et al. 1997) appears to be consistent with the recent CO nova calculations (José et al. 2004).

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