Condensation of SiC Stardust in CO Nova Outbursts

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Abstract

This study on presolar grains compares high-precision isotopic compositions of individual SiC grains with low $^{12}$C/$^{13}$C ratios, low $^{14}$N/$^{15}$N ratios, large $^{30}$Si excesses, and high $^{26}$Al/$^{27}$Al ratios, all available in the presolar grain database, to new CO nova models with white dwarf (WD) masses from 0.6 to 1.35 $M_{\odot}$. The models were designed to match the Large Binocular Telescope high-dispersion spectra acquired for nova V5668 Sgr. These CO nova models provide elemental abundances up to calcium and include mixing of WD material into the accreted material in a binary star system under several scenarios, including one where mixing occurs only after temperatures $>7 \times 10^7$ K are achieved during a thermonuclear runaway (TNR). The 0.8–1.35 $M_{\odot}$ simulations where 25% of the WD core matter mixes with 75% of the accreted material (assumed solar) from its binary companion after the TNR has begun provide the best fits to the measured isotopic data in four presolar grains. One grain matches the 50% accreted 50% solar 1.35 $M_{\odot}$ simulation. For these five presolar grains, less than 25% of solar system material is required to be mixed with the CO nova ejecta to account for the grains’ compositions. Thus, our study reports evidence of pure CO nova ejecta material in meteorites. Finally, we speculate that SiC grains can form in the winds of cool and dense CO novae, where the criterion $C > O$ may not be locally imposed, and thus nova winds can be chemically inhomogeneous.

Key words: meteorites, meteors, meteoroids – novae, cataclysmic variables – nuclear reactions, nucleosynthesis, abundances – supernovae: general

1. Introduction

Presolar grains are minute specks of rare dust grains in pristine meteorites. Tens of thousands of presolar SiC grains have been identified to date by their exotic isotopic compositions in major and trace elements (Zinner 2014; Nittler & Cielsa 2016). These compositions are diagnostic of the gaseous environments in several stellar sites, where the dust grains condensed, and complement the radio and infrared observations of these stellar sites.

Presolar SiC grains are the most widely studied because they can be chemically extracted from meteorites and exhibit high concentrations of trace and rare earth elements. The SiC in both the large (1.8–3.7 μm) and small (0.5–0.65 μm) size fractions have been extensively investigated (e.g., Amari et al. 1994; Hoppe et al. 2010). Therefore, SiC grains provide unique opportunities to understand stellar evolution and nucleosynthesis, which has improved our understanding of processes in circumstellar envelopes and explosive environments, since their isolation in the 1980s (Bernatowicz et al. 1987; Anders & Zinner 1993; Amari et al. 1994). The carbon, nitrogen, and silicon isotopic compositions of the mainstream SiC grains and SiC X grains strongly affirm their origins in low-mass, solar metallicity, asymptotic giant branch stars, and core-collapse supernovae, respectively (e.g., Hoppe et al. 1996; Nittler et al. 1996).

The stellar source has been under intense debate for some SiC grain types, e.g., SiC grains with low $^{12}$C/$^{13}$C ratios <10, low $^{14}$N/$^{15}$N isotope ratios in the range ~5–20, large $^{30}$Si excesses, and high $^{26}$Al/$^{27}$Al ratios. The grains with these unique isotopic compositions were argued to have formed in ONe novae (“nova candidates,” henceforth; Amari et al. 2001) based on the model fits to several isotope systems (José & Hernanz 1998; José et al. 1999). The grain compositions require mixing of material synthesized in the nova outburst with isotopically close-to-solar system material. More specifically, the mixing of material between the white dwarf (WD) masses 1.15 and 1.25 $M_{\odot}$ with >90% solar/terrestrial values were mandatory to account for the carbon, nitrogen, silicon, and aluminum isotopic ratios of the nova candidate grains (Amari et al. 2001). The implications from the Amari et al. (2001) study were twofold: first, the nova candidate grains were primarily from a binary system composed of the WD and a companion star on the main sequence. Second, the SiC grains probably formed from the outermost C-rich (C > O) ejecta blanket, very soon after the star exploded as a nova.

All these inferences about nova candidate grains are in stark contrast with what is known from observations of novae. First, CO novae are more abundant (70%–80%) than ONe novae and second, they are hypothesized to produce dust grains more efficiently (e.g., Gehrz et al. 1986; Mason et al. 1996).

Nittler & Hoppe (2005) disputed the origins of the nova candidate grains. They argued for supernova origins of some grains identified by Amari et al. (2001) that exhibited $^{47,48}$Ti anomalies and $^{44}$Ca excesses. For example, one grain, 334-2 (Nittler & Hoppe 2005), which exhibits low $^{12}$C/$^{13}$C and $^{14}$N/$^{15}$N ratios, has Si and Ca isotopic compositions akin to SiC X grains. $^{44}$Ca enrichment in this grain points toward the initial presence of $^{44}$Ti, only synthesized in supernovae. All these factors combined indicate that this particular grain, originally argued to have a nova origin, should be reclassified as a supernova grain. Another grain, 151-4, that exhibits a 47Ti excess was argued to have an origin in a $\sim 1.2 M_{\odot}$ ONe nova. Although the origins of $^{47}$Ti are uncertain, $^{47}$Ti anomalies can originate in both Type II supernovae (SNe II; Nittler & Hoppe 2005) and Type Ia supernovae (Woosley & Weaver 1994). Nittler & Hoppe (2005) argued that the $^{47}$Ti excesses, or in general, Ti isotopic anomalies, can be produced only at high temperatures that may not be attained in nova explosions.

The study inferred that grain 151-4 with $^{47}$Ti excesses formed in an astrophysical setting, other than novae. This study clearly
indicates the need for measuring multiple isotopic systems in the same grain, and a comparison between models and laboratory measurements can yield improved results when the number of isotopic systems measured in the same grain is large.

New nova simulations using the more precise thermonuclear rate of $^{33}$S(p, $\gamma$)$^{34}$S constrained the $^{32}$S/$^{33}$S ratios in nova models to 110–130, whereas recent type II supernova models predict $^{32}$S/$^{33}$S ratios of 130–200, so sulfur isotopes were claimed as the means to distinguish between grains of nova and supernova origin (Parikh et al. 2014). This hypothesis led to measurements of sulfur isotopes in seven nova candidate grains, none of which exhibit $^{32}$S/$^{33}$S ratios in the range speculated by Parikh et al. (2014) ($^{32}$S/$^{33}$S = 110–130). Six grains show depletions of $^{33}$S, while one shows $\delta^{33}$S/$^{32}$S = 48 ± 334 (Liu et al. 2016; delta notation is defined as

$$\delta^{33}S = \left( \frac{^{33}S}{^{32}S} \right)_{\text{sample}} - 1 \right) \times 1000%$$

Lower than solar $^{34}$S/$^{32}$S ratios in two of them ($\delta^{34}S/^{32}S = -542 \pm 175; -394 \pm 106$) were used as evidence for ruling out their origins in ONe novae (Liu et al. 2016). Liu et al. (2016) further discussed that several nova candidate grains could have their origins in SNe II, and an unambiguous assignment may never be possible because proton capture in both these explosive H burning environments would produce p-rich radionuclides. More recently, Iliadis et al. (2018) used a different strategy to constrain the origin of nova grains by simulating nova grain compositions over a large parameter space, including reaction rates, peak temperature, density, and decay time. A comparison of these simulated compositions to the presolar grain measurements shows that only a small subset (16%) of nova candidate grains exhibits isotopic signatures consistent with a nova origin. This strategy works better for grains that have more isotopic ratios measured, i.e., the larger the number of isotope ratios known, the higher the chance of getting an acceptable solution to their simulations.

In this paper, we use the isotopic abundances from recent CO nova simulations from S. Starrfield et al. (2018, in preparation) to compare to the existing database of putative nova grains. Because these simulations attempt to match the peak luminosities and ejection velocities observed in nova explosions, they are more diagnostic of actual environments. The differences between the models described in Iliadis et al. (2018) and S. Starrfield et al. (2018, in preparation) are discussed in Section 2. Some SiC nova candidate grain compositions can be well explained by these new CO nova simulations, therefore CO novae probably has injected dust grains into the protosolar molecular cloud. Carbonaceous dust grains have been observed to form O-rich binary stars, although the premise C > O may not be satisfied. All types of dust (SiC, silicates, hydrocarbons) form at different times during a single nova outburst probably because CO formation does not go to completion and nova ejecta have large abundance gradients (Gehrz et al. 1992).

### 2. Nova Models

The calculations reported in S. Starrfield et al. (2018, in preparation) were done using NOVA. NOVA is a one-dimensional, fully implicit, Lagrangian hydrodynamic computer code described in Starrfield et al. (1997, 2009, and references therein). The simulations that produced the isotopic abundances used in this paper were done with 150 mass zones and convective mixing was done with the Arnett et al. (2010) algorithm. They used a mixing-length to a scale height ratio of 4. In contrast to earlier work, they used the Starlib reaction rate library (Sallaska et al. 2013). The simulations were done for CO (carbon 50% by mass and oxygen 50% by mass) WD masses of 0.6, 0.8, 1.0, 1.15, 1.25, and 1.35 $M_\odot$ with a mass accretion rate of $2 \times 10^{-9} M_\odot$ yr$^{-1}$ and an initial luminosity of $4 \times 10^{34} L_\odot$. For all cases the tabulated abundances were obtained from that fraction of the envelope that, as a result of the thermonuclear runaway (TNR), had reached escape velocity and was optically thin. There are three sets of simulations reported in S. Starrfield et al. (2018, in preparation). The initial WD structure was the same for all the simulations, only the composition of the accreting material was changed. The first set of simulations assumed that the accreting material had mixed with the WD material from the beginning (MFB). This is the same assumption as in all the previous studies by Starrfield and collaborators. Two separate compositions were used (all abundances are mass fractions): either 25% core material and 75% solar matter (25%–75%) or 50% core material and 50% solar (50–50) matter (Lodders 2003). These simulations were followed through the peak of the TNR and for a sufficiently long time after to determine the amount of ejected material and its velocity. These simulations (MFB 25–75 and MFB 50–50 are plotted in Figures 1 and 2) were in poor agreement with the carbon, nitrogen, and silicon isotope data in SiC grains. In addition, these simulations do not eject sufficient material with significant velocities to agree with the observations of nova explosions (Bode & Evans 2008).

The second set of simulations involved accreting just solar material and these were also followed through the explosion. The third set assumed that mixing of the core with the envelope did not occur until the peak temperature in the TNR (initiated with the pure solar mixture) had reached about $7 \times 10^7 K$. At this time the composition of the accreted layers was instantaneously switched to either the 25–75 mixture or the 50–50 mixture. As reported in S. Starrfield et al. (2018, in preparation), the simulations with the new mixture took only a few seconds to adjust and the resulting structure was followed through the peak of the TNR to determine the amount of ejected matter and velocities. The isotopic abundances in the ejected material were then tabulated, used for the studies in the current work, and reported in S. Starrfield et al. (2018, in preparation). The initial $^{12}$C abundance (from Lodders et al. 2009) makes a difference when the TNR is reached and the simulations with more $^{12}$C evolve faster with less accreted mass. The mixed core-accreted compositions in our simulations are composed of either 25% WD core and 75% solar material or 50% WD core and 50% accreted material and are referred to as MDTNR 25–75 and MDTNR 50–50, respectively. The temperatures reached in the deepest H-rich zones increase with the WD mass, and those for the 1.35 $M_\odot$ MDTNR 25–75 and MDTNR 50–50 models are 3.4 $\times 10^6 K$ and 6 $\times 10^6 K$, respectively (S. Starrfield et al. 2018, in preparation). Furthermore, the amount of $^{12}$C is less in the MDTNR 25–75 simulations, which results in a longer decline to quiescence.

Iliadis et al. (2018) used a totally different procedure and it is difficult to compare its results with our study. Instead of doing a full evolutionary simulation, they chose values for the peak temperature and density, and then assumed an exponential
decrease in those values as a function of time. The study assumed a WD mass of 1.0\,M_{\odot}, luminosity of 10^{-2}\,L_{\odot}, accreted solar-like material at a mass accretion rate of 2 \times 10^{-10}\,M_{\odot}\,\text{yr}^{-1}, and MFB with a 50–50 mixture. Iliadis et al. (2018) compared their results to one simulation done with SHIVA (José & Hernanz 1998) and achieved reasonable agreement (factor of 2) between their method and the SHIVA study (see Figure 2 of Iliadis et al. 2018). They then varied both the reaction rates and the values of temperature, density, and decay time using a Monte Carlo technique; compared their results to one simulation done with MDTNR and MFB models have also been plotted, and mixing lines between WD masses 0.8–1.35\,M_{\odot}, and solar system material assuming terrestrial ratios, hereafter are shown by lines of different colors. For the MDTNR model with a WD mass of 1.15\,M_{\odot}, the proportion of nova ejecta is written next to the mixing lines. Except for AF15bC-126-3, G240-1, G1697, Ag2, Ag2_6, G270_2, M2-A4-G672, M2-A5-G1211, M1-A8-G145, KJD-1-11-5, and KJD-3-23-5 (Table 2), all the grains can be quantitatively explained by the MDTNR 25–75 and 50–50 models.

![Figure 1. 12C/13C and 14N/15N ratios of nova candidate grains from the literature (Hoppe et al. 1996, 2018; Gao & Nittler 1997; Amari et al. 2001; Nittler & Alexander 2003; Nittler & Hoppe 2005; Liu et al. 2016, 2017) plotted in black. The SiC grains with a higher probability of being products of CO novae, based on Iliadis et al. (2018), are shown in orange (I-18). This figure includes five SiC AB grains from Liu et al. (2017, referred to as L-17). The black and orange grains with yellow outlines do not fit the simulations. Simulations from MDTNR and MFB models have also been plotted, and mixing lines between WD masses 0.8–1.35\,M_{\odot}, and solar system material assuming terrestrial ratios, hereafter are shown by lines of different colors. For the MDTNR model with a WD mass of 1.15\,M_{\odot}, the proportion of nova ejecta is written next to the mixing lines. Except for AF15bC-126-3, G240-1, G1697, Ag2, Ag2_6, G270_2, M2-A4-G672, M2-A5-G1211, M1-A8-G145, KJD-1-11-5, and KJD-3-23-5 (Table 2), all the grains can be quantitatively explained by the MDTNR 25–75 and 50–50 models.](image_url)

3. Comparisons with Presolar Grains

Table 1 lists the carbon and nitrogen isotope ratios of thirty presolar SiC grains obtained from the literature (Hoppe et al. 1996, 2018; Gao & Nittler 1997; Amari et al. 2001; Nittler & Alexander 2003; Nittler & Hoppe 2005; Liu et al. 2016, 2017). Three of those grains do not have either carbon or nitrogen isotopic compositions, so Figure 1 shows only the compositions of 27 presolar SiC grains, including the six SiC grains with the highest probability of being nova condensates (Iliadis et al. 2018) in orange. The theoretically predicted CO models are plotted with different symbols. Except for the 0.6\,M_{\odot}, MFB 50–50 simulation, all remaining CO nova simulations are plotted in the third quadrant (lower left) of the carbon–nitrogen isotope space (Figure 1). These new CO results are in stark contrast to the predictions from prior studies (e.g., José et al. 2004). CO results from José et al. (2004) spanned a large range in 14N/15N ratios from 5 to 50,000. One isotopic compositions from José et al. (2004), on the other hand, plot approximately at the location of the CO model simulations described here.

The presolar SiC data fall in between the terrestrial ratios and compositions of the MDTNR CO nova simulations predominately in the lower left in Figure 1. Mixing between the products of nucleosynthesis in the nova explosion and...
isotopically close-to-solar material is thus required to explain the grain compositions. Mixing lines for the MDTNR 25–75 and 50–50 models with 0.8–1.35 $M_\odot$ WD masses are shown in Figure 1. We consider that a grain composition matches a simulation if the mixing lines fall within $<2$–$4$ times the errors on the measured compositions. Based on this assumption, the MDTNR 25–75 and 50–50 models with WD mass 1.00–1.35 $M_\odot$ can quantitatively explain the carbon and nitrogen isotopic data for a majority (17 out of 27) of the SiC grains (without yellow outlines in Figure 1), including four grains with the highest probability of being nova grains (Iliadis et al. 2018). In several cases, simulations with different WD masses can explain a grain’s carbon and nitrogen isotopic compositions simultaneously (Figure 1). Table 2 shows all the models that can reproduce the grains’ compositions. The individual cells in Table 2 are in bold or italics to identify grains where 4–5 isotope ratios fit the simulations. The grains whose compositions can be explained by the mixing lines mostly require a larger proportion of the material from the nova. The proportion of nova ejecta varies from $\sim$80% to $>95$% for a majority of the grains, in sharp contrast to previous work. Previous work required $<5$% of the material to be from the nova ejecta (e.g., Amari et al. 2001). The proportion of nova ejecta to be mixed with the solar system material is listed (in percentage) for the MDTNR 25–75 simulation with 1.15 $M_\odot$ WD mass because it can explain a large number of nova candidate compositions (Figure 1). Several grains that lie on the 1.15 $M_\odot$ mixing line require 90% material from the nova ejecta. The highly plausible grain M11-151-4 that plots on the MDTNR 25–75 $1.15 M_\odot$ mixing line requires $\sim$95% of material from the nova ejecta. Finally, 11 SiC grains (black and orange symbols with yellow outlines in Figure 1) cannot be explained by any of the CO models. These include AF15bC-126-3, G240-1, G1697, Ag2, Ag2_6, G270_2, M2-A4-G672, M2-A5-G1211, M1-A8-G145, KJD-1-11-5, and KJD-3-23-5 (Table 2).

The consistency between the grain data and simulations qualitatively does not break down when we consider other isotopic systems. A comparison of the silicon isotopes of 29 SiC grains (Hoppe et al. 1996, 2018; Gao & Nittler 1997; Amari et al. 2001; Nittler & Alexander 2003; Nittler & Hoppe 2005; Liu et al. 2016, 2017) and nova models indicates that 10 SiC grains with close-to-solar $^{28}\text{Si}/^{29}\text{Si}$ ratios and some $^{30}\text{Si}$ enrichments match the silicon isotope compositions of the low-mass (0.6–0.8 $M_\odot$) MDTNR simulations (Figure 2, 2-inset, Table 2). More precisely, these SiC grains can be explained by the MDTNR 25–75 CO simulations with no mixing between the nova and solar system materials. Five SiC grains with correlated $^{29}\text{Si}$- and $^{30}\text{Si}$ enrichments (third quadrant of the Si isotope plot) fall on the MDTNR 50–50 model with the high WD mass of 1.35 $M_\odot$. These grains require variable amounts of nova ejecta from $\sim$50%–80% (Figure 2). Eight SiC grains with
References. (a) Hoppe et al. (1996), (b) Amari et al. (2001), (c) Nittler & Alexander (2003), (d) Nittler & Hoppe (2005), (e) Liu et al. (2016), (f) Liu et al. (2017), (g) Hoppe et al. (2018).
Table 2
Fits to the Carbon, Nitrogen, Silicon, Sulfur, and Aluminum Isotopic Data Using New Nova Models

| Grain       | MDTNR 25–75                  | MDTNR 50–50                  | No Good Fit(s) | No Data |
|-------------|-------------------------------|-------------------------------|----------------|---------|
|             | 1.35  | 1.25  | 1.15  | 1.00  | 0.8   | 0.6   | 1.35  | 1.25  | 1.15  | 1.00  | 0.8   | 0.6   |         |         |
| KJC11 (a)   | C, N  | C, N  |       |       |       |       | C, N  |       |       |       |       |       | Si, S, Al |         |
| KJGM4C-100-3 (b) |       |       |       |       |       |       |       |       |       |       |       |       |         |         |
| KJGM4C-311-6 (b) |       |       |       |       |       |       |       |       |       |       |       |       |         |         |
| AF15bC-126-3 (b) | Si    |       |       |       |       |       |       |       |       |       |       |       | C, N, S, Al |         |
| AF15bB-429-3 (b) |       |       |       |       |       |       |       |       |       |       |       |       |         |         |
| M26a-53-8e (c) |       |       |       |       |       |       |       |       |       |       |       |       |         |         |
| M11-151-4 (d) | Al    | C, N  | Si, S |       |       |       | C, N  | Si    |       |       |       |       |         |         |
| M11-334-2 (d) | C, N  | C, N  |       |       |       |       | C, N  | C, N  | Al    | Al    |       |       | S, Al    |         |
| M11-347-4 (d) |       |       |       |       |       |       |       |       |       |       |       |       |         |         |
| G1342 (e)   |       |       |       |       |       |       | C, N  | Si    |       |       |       |       | Al, S    |         |
| GAB (e)     |       |       |       |       |       |       |       |       |       |       |       |       |         |         |
| G240-1 (e)  |       |       |       |       |       |       |       |       |       |       |       |       |         |         |
| G1748 (e)   |       |       |       |       |       |       |       |       |       |       |       |       |         |         |
| G283 (e)    | C, N  | C, N  | Si, S |       |       |       | C, N  | Si    |       |       |       |       |         |         |
| G1614 (e)   |       |       |       |       |       |       |       |       |       |       |       |       |         |         |
| G1697 (e)   | Si    | Si    |       |       |       |       |       |       |       |       |       |       | C, N, Al |         |
| G278 (e)    |       |       |       |       |       |       |       |       |       |       |       |       | S, Al    |         |
| Ag2 (e)     | Si    | S     |       |       |       |       |       |       |       |       |       |       |         |         |
| Ag2_6 (e)   |       |       |       |       |       |       |       |       |       |       |       |       |         |         |
| M2-A1-G410 (f)       |       |       |       |       |       |       |       |       |       |       |       |       |         |         |
| M2-A3-G208 (f)       |       |       |       |       |       |       |       |       |       |       |       |       |         |         |
| M2-A1-G114 (f)       |       |       |       |       |       |       |       |       |       |       |       |       |         |         |
| M2-A5-G209 (f)       |       |       |       |       |       |       |       |       |       |       |       |       |         |         |
| M2-A4-G672 (f)       |       |       |       |       |       |       |       |       |       |       |       |       |         |         |
| M2-A4-G27 (f)        |       |       |       |       |       |       |       |       |       |       |       |       |         |         |
| M2-A5-G1211 (f)      |       |       |       |       |       |       |       |       |       |       |       |       |         |         |
| M1-A9-G145 (f)       |       |       |       |       |       |       |       |       |       |       |       |       |         |         |
| KJD-1-11-5 (g)       |       |       |       |       |       |       |       |       |       |       |       |       |         |         |
| KJD-3-23-5 (g)       |       |       |       |       |       |       |       |       |       |       |       |       |         |         |

Note. Grains where five isotopic ratios are a good match are in bold. Grains where four isotopic ratios are a good match are in *italics*. Si and S isotopes are comprised of two ratios each.

References. (a) Hoppe et al. (1996), (b) Amari et al. (2001), (c) Nittler & Alexander (2003), (d) Nittler & Hoppe (2005), (e) Liu et al. (2016), (f) Liu et al. (2017), (g) Hoppe et al. (2018).
other factor that we are aware of are the systematic errors associated with sample preparation and difficulties during isotopic measurements of contaminated grains. For example, sulfur isotope data of presolar SiC grains can be contaminated with terrestrial and meteoritic contributions. In addition, significant quantities of sulfur are not expected to condense into SiC. The observed $^{32}\text{S}$ excesses in SiC X grains of supernova origin are likely due to the decay of radioactive $^{32}\text{Si}$ (Pignatari et al. 2013). This pure $^{32}\text{S}$ component is diluted by sulfur contamination that must have lowered the true anomalies. Despite these uncertainties, the sulfur isotopic compositions of three SiC grains match the compositions of the simulations well (Figure 3, Table 2).

4. Discussion

4.1. Nova Grains in the Presolar Grain Inventory

Because any meaningful comparison of stellar model predictions with presolar grains should be based on multi-element isotope data of individual grains, we list all simulations that fit carbon, nitrogen, silicon, sulfur, and aluminum isotope data simultaneously for all the grains in Table 2. Getting a quantitative solution considering carbon and nitrogen only was not difficult but getting a good fit to the silicon data for the same simulation did not occur in the majority of cases. Only eight grain compositions can be reproduced by at least four isotopic ratios and they have been included in Table 3. Some of these grains require several different scenarios. Next, we did mixing calculations between the terrestrial ratios and nova compositions and calculated the contribution from the nova ejecta in each case. The contribution from the nova ejecta that will explain the SiC isotopic compositions is listed in Table 3.

We consider each of these eight grains in more detail below. We designate a grain to be a nova condensate if the proportion of nova contributions from the mixing calculations is similar (within 25%) for any three isotope ratios. Note that the dispersions in the output of the model simulations are unknown at present but can be as large as 50% (e.g., by changing the WD mass), so grains with proportions of nova contributions that differ by 50% are considered plausible nova grains (maybe category). These are our criteria for the discussion below.

4.1.1. M11-151-4 and M2-A1-G410

These two grains fit the MDTNR 25–75 simulations, with WD mass between 0.8 and 1.15 $M_\odot$. Both require $>88%$ matter from the nova to explain their carbon and nitrogen isotope compositions. M11-151-4 requires 75% of nova contributions to match silicon isotopes and 96% for $^{26}\text{Al}/^{27}\text{Al}$ isotope ratio, which certainly makes this grain a nova grain. For the grain M2-A1-G410, two simulations (Table 3) gave promising results. The MDTNR 25–75 1.00 $M_\odot$ simulation required a 20% contribution from the nova to explain the grain’s silicon isotopic composition, which was used to rule out this scenario. Alternatively, the simulation MDTNR 25–75 0.8 $M_\odot$ matches the carbon, nitrogen, silicon, and aluminum isotope ratios very well, with contributions from the nova being greater than 90%. Neither of these grains have sulfur isotope data but considering that five isotope ratios are well matched for the MDTNR 25–75 0.8 $M_\odot$ simulation, our criteria suggest that these are produced in nova ejecta.

Grain M11-151-4 shows $^{47}\text{Ti}$ excesses, which were interpreted by Nittler & Hoppe (2005) to be a supernova signature because of the inability of novae to reach high enough
temperatures. However, our $1.35 M_e$ simulations are able to achieve sufficiently high temperatures that make production of $^{47}$Ti possible.

4.1.2. G1342

The simulation MDTNR 50–50 with a high-mass ($1.35 M_e$) WD explains the carbon and nitrogen isotope compositions of this grain and requires a 98% contribution from the nova. This grain has no sulfur data and we were unable to get a good fit for aluminum from this simulation. The fit for silicon isotopes works, but the percentage contribution from the nova is about 55%. Although the uncertainties in the model parameters can be large (∼50%), we consider this grain to be in the “maybe” category, keeping our criteria in mind.

4.1.3. GAB

This grain matches both MDTNR 25–75 and MDTNR 50–50 simulations with a WD mass of $1.00 M_e$. For both simulations, the nova contribution that explains the carbon and nitrogen isotopic compositions is ∼98%, and that for sulfur isotope ratios is 100%. Although no good fits for silicon or aluminum isotope ratios could be attained in these simulations, the fact that almost identical amounts of material are required from the nova simulation makes it a nova grain. Note that this is the only grain in our list (Table 3) where two simulations are able to reproduce the grains’ compositions.

4.1.4. G283

The carbon and nitrogen isotopic compositions of grain G283 can be well explained by four different simulations, MDTNR 25–75 $1.00 M_e$, MDTNR 25–75 $1.25 M_e$, MDTNR 25–75 1.35 $M_e$, and MDTNR 50–50 1.25 $M_e$. Only the MDTNR 25–75 1.35 $M_e$ simulation provides a good fit to the carbon, nitrogen, and aluminum isotope ratios. The remaining simulations do not provide good fits to the aluminum isotope ratios and the contribution for silicon isotopes is <20% in all cases. Silicon is a major element in the grain and the inability of the simulations to provide a good fit is not understood. But based on our criteria, we consider G283 a nova grain.

4.1.5. G1748, M2-A1-G114, and M2-A5-G269

For these three grains, the contribution of >80% nova matter is necessary to explain the carbon and nitrogen isotopic compositions. However, for silicon, the same models only require ∼10%–20% of matter from the nova ejecta. Sulfur and aluminum isotopes have not been measured for M2-A1-G114 and M2-A5-G269. Furthermore, a good fit for aluminum isotope ratios in grain G1748 could not be achieved. Therefore, we do not consider these grains to be nova grains, and other stellar sites need to be considered.

Therefore, this detailed comparison between the nova models and grain compositions has allowed us to rule out several nova candidate grains and identify four grains, namely M11-151-4, M2-A1-G410, GAB, and G283, that are likely true nova condensates. SiC grain G1342 is currently placed in the “maybe” category, and uncertainties in models need to be investigated to ascertain its origins. Only grain M11-151-4 from Nittler & Hoppe (2005) is included in Iliadis et al. (2018) as a high-probability CO nova grain. Thus, four SiC grains can be explained by 25–75 MDTNR models with WD masses of 0.8, 1.00, 1.15, and 1.35 $M_e$. The MDTNR 50–50 simulation in the high WD mass range (1.35 $M_e$) works well too.
4.2. Carbon-rich Grain Formation in CO Novae

Although earlier work (José et al. 2004; José & Hernanz 2007) showed that CO novae should exhibit limited nuclear activity beyond the CNO region because of the moderate peak temperatures achieved during the explosion, and the lack of seed nuclei of the heavier masses, the new models presented here contradict those results. The primary differences between the two studies (Iliadis et al. 2018 study that used Jose models; S. Starrfield et al. 2018, in preparation) were presented earlier. High $^{12}$C/$^{1}$H ratios result in an increase in the rate of energy production during the CNO cycle, which in turn produces high temperatures in the nuclear burning region (S. Starrfield et al. 2018, in preparation). Thus, good agreement between the new MDTNR CO nova simulations and a small selection (<20%) of the presolar SiC grain data is achieved and nova grains form a small, yet significant fraction of the presolar grain inventory.

Equilibrium condensation calculations require that the carbon-rich grains condense if C > O and oxide/silicate grains condense if C < O. Because both oxide and carbon-bearing dust grains have been reported through IR spectroscopy of nova outbursts (Gehrz et al. 1992, 1995; Mason et al. 1996, 1997), this may imply that locally the C < O criterion may not be met, allowing for chemical heterogeneity in the nova ejecta. It was suggested that oxygen-rich supernova environments can form graphite stardust, depending strongly on the density of the CO-bearing gas and the production of free carbon by thermal radiation and heating by radionuclides (Deneault et al. 2006). A recent model by Derdziński et al. (2016) explored this possibility and investigated the location and mechanism by which dust grains can form and survive the intense UV and IR radiation in a nova explosion. They argued that the high-energy particles accelerated at the shock have the potential to destroy the CO molecule that would allow for the formation of carbon-bearing dust grains in the carbon-poor, cool, dense shells following the shocked gas. Alternatively, dust condensation can proceed under non-equilibrium conditions such that only a small fraction of the carbon ends up in the CO molecule (Evans et al. 1996), and lead to specific conditions where carbonaceous and oxide grains can condense simultaneously. Such non-equilibrium conditions can occur due to the presence of intermediate-mass elements, such as aluminum, calcium, magnesium, or silicon that may dramatically alter the stellar environment and allow the formation of carbon-rich dust even in a slightly O-rich environment (José et al. 2004, 2016). Finally, the timing of the formation of carbon- and oxygen-rich dust grains can be different.

For example, carbon-rich dust was identified first, followed later by silicate formation in several novae (Gehrz et al. 1992; Evans et al. 1997; Mason et al. 1998; Sakon et al. 2016). These observations corroborate with the models of José et al. (2016) where chemical profiles with varying C/O ratios resulted in carbon-rich outer layers and oxygen-rich inner layers. Therefore, SiC grain condensation can occur via several ways, namely in the winds of carbon-rich outer layers, carbon-poor dust shells produced by particle irradiation, or proceed via kinetic effects during mixing of the different shells in the nova winds. The efficiency with which grain formation could occur in these situations is poorly constrained.

4.3. SiC AB Grains and C2

This study has implications for other types of SiC grains that have been classified in earlier work as SiC AB and C2 grains. SiC grains classified as Type C2s have carbon and nitrogen isotope compositions similar to the nova candidate grains ($^{12}$C/$^{13}$C = 1–6; $^{14}$N/$^{15}$N = 7–13), but have correlated enrichments in $^{29,30}$Si compared to $^{28}$Si (Liu et al. 2016). Our study included four grains as Type C2 (G278, G1342, GAB, G240-1), which were argued to not form in nova ejecta because the Si isotopic signatures of these grains (Liu et al. 2016) did not agree with ONe nova models (José et al. 2004; José & Hernanz 2007). However, the new simulations described here fit these grains’ carbon, nitrogen, and sulfur isotopic compositions very well. However, three of these four grains (GAB, G1342, G249–1 in Figure 4) show low $^{26}$Al/$^{27}$Al isotopic ratios that are not explained by the MDTNR models. The grain GAB, however, fits the MDTNR simulations (Table 3). Thus, a section of SiC C2 grains can have nova origins.

Another grain type whose origins need to be evaluated in the light of these new nova models is the SiC AB grains that
have $^{15}$N enrichments ($^{14}$N/$^{15}$N $\sim$ 4–200), low $^{12}$C/$^{13}$C ratios ($^{12}$C/$^{13}$C $\sim$ 1–10), and enrichments in heavy Si isotopes up to about 200‰ (Amari et al. 2001). These grains typically show a very large range in $^{26}$Al/$^{27}$Al ratios from $\sim$4 $\times$ 10^{-5} to 2 $\times$ 10^{-2}. The carbon and nitrogen isotopic compositions of five AB grains, namely M1-A5-G1424, M3-G1134, M3-G1332, M3-G319, and M3-G489 (Figure 1; Liu et al. 2017) can be explained by the 0.6–0.8 $M_\odot$ MDTNR 25–75 CO nova simulations. Because these same grains have close-to-solar silicon isotope ratios, the same low-mass MDTNR simulations can explain their silicon isotope compositions with 100% nova ejecta material (Figure 2). But these grains have $^{26}$Al/$^{27}$Al ratios even lower than the Type C2 grains described above (Figure 4), therefore their aluminum isotope compositions cannot be explained by the CO nova models.

Based on these observations of aluminum isotope ratios, we argue that grains whose carbon, nitrogen, silicon, and sulfur isotopes fall within the simulated models and those that exhibit $^{26}$Al/$^{27}$Al ratios $>6 \times 10^{-2}$ are the most likely nova grains. We argue, however, that the $^{26}$Al/$^{27}$Al ratios alone cannot be diagnostic of nova origins, therefore, we cannot rule out a nova origin for grains with low $^{26}$Al/$^{27}$Al ratios, observed in the SiC AB and C2 grains. Novae with an abundance of seed NeNaMgAl nuclei could produce large abundances of $^{26}$Al. $^{26}$Al synthesis requires peak temperatures on the order of (2–3) $\times$ 10^8 K (Ward & Fowler 1980) and such temperatures are achievable in the CO models described here. But if the abundance of Mg seed nuclei in CO WD is low, the production of $^{26}$Al can be hindered. Whether there are mechanisms that allow for low $^{26}$Al/$^{27}$Al ratios in CO nova needs to be further investigated.

4.4. The Origin of Grain SiC070, with Known Carbon, Nitrogen, Silicon, and $^4$He/$^{20}$Ne Isotope Ratios

Only one presolar grain, SiC070, with a low $^{12}$C/$^{13}$C ratio, along with He and Ne isotopic compositions, has been reported in the literature to date (Heck et al. 2007). Both theoretical and observational evidence suggest that novae may be an important source of the radioactive isotope $^6$He, which is involved in the production of the $^{26}$Ne (Ne-E) measured in SiC grains. The $^4$He/$^{20}$Ne ratio of the grain SiC070 is 60; its low $^{12}$C/$^{13}$C ratio of 3.5 was used to identify it as a SiC AB grain (Heck et al. 2007). Because the nova models described here provide the He and Ne abundances, we compared the grain’s carbon and noble gas compositions to the simulations. The composition of this grain can be explained best by the 1.15 $M_\odot$ MDTNR 25–75 model: mixing 96% of nova ejecta to 4% solar system material produces a $^{12}$C/$^{13}$C ratio = 3.5 and assuming no solar system contribution for the He/Ne isotope ratios, we get $^4$He/$^{20}$Ne = 67, which is very close to the grains’ composition. However, neither its nitrogen nor silicon isotope compositions can be explained by the 1.15 $M_\odot$ MDTNR 25–75 simulation or any other simulation. This gives us great confidence that SiC070 does not have a CO nova origin. Additional Ne isotopic measurements of gas-rich SiC grains with low $^{12}$C/$^{13}$C ratios are required for suitable comparisons to the models in the future.

5. Conclusions

This work describes the results from new nova models in order to understand the progeny of presolar grains with low $^{12}$C/$^{13}$C ratios (<10), low $^{14}$N/$^{15}$N isotope ratios in the range $\sim$5–20, large $^{30}$Si excesses, and high $^{26}$Al/$^{27}$Al ratios. We explored several CO simulations where the mixing conditions were varied, and quantitative mixing models were carried out.

The simulations elucidate the puzzling isotopic compositions of the carbon-rich presolar grains. The comparisons of the simulations to the SiC grains show two major outcomes. First, the 0.8–1.35 $M_\odot$ CO MDTNR 25–75 models, where mixing between the core and accreted material in the binary star system occurs after TNR is initiated, can explain the isotope compositions of four presolar grains quantitatively. One grain requires the MDTNR 50–50 simulation with 1.35 $M_\odot$ WD. Second, the grain compositions require $\sim$25% of solar system material to reproduce the grains’ compositions, which confirms that nova dust grains are a component of the presolar grain inventory. Now that isotopic compositions of carbon, nitrogen, silicon, sulfur, and aluminum compositions in the carbon-rich nova grains have been constrained, further work is needed to understand the nature of oxygen-rich dust produced in the nova explosion and the consequences on grain compositions due to episodic mass loss. In addition, the stellar sites of most of the grains that do not match the CO nova simulations need to be investigated. For example, supernova models by Pignatari et al. (2015) that simulate core-collapse supernovae (CCSNe) in a 25 $M_\odot$, Z = 0.02 progenitor star, where the star undergoes a rapid explosion at high kinetic energies of (4–7) $\times$ 10^{51} erg or recent three-dimensional models of asymmetric SNe (Schulte et al. 2019) could be invoked to solve the origins of the SiC grains that are not nova condensates. This work is extremely relevant to the planetary science community because it enhances our understanding of the solar system environment prior to its formation. Injection of compositionally diverse presolar material from CO novae probably occurred in the early solar system.

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