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The origin of presolar nova grains

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Abstract–Infrared observations reveal that classical novae often form dust in their expanding shells ejected into the interstellar medium as a consequence of violent outbursts. Recent experimental efforts have led to the identification of presolar nova candidate grains from the Acfer 094 and Murchison meteorites. Recently, however, concerns have been raised about the stellar paternity of these grains by new measurements on another sample of SiC grains: these grains are characterized by $^{12}C/^{13}C$ and $^{14}N/^{15}N$ ratios similar to the ones reported for the nova grains, but a number of different imprints suggest that a possible supernova origin cannot be excluded. Here we review the predicted nucleosynthetic imprints accompanying nova explosions and discuss the chances to synthesize heavier species, such as titanium, in nova-like events.

PRESOLAR GRAINS

Presolar grains are tiny pieces of stardust found in primitive meteorites and interplanetary dust particles. They are characterized by huge isotopic anomalies linked to a suite of nucleosynthetic processes that took place in their parent stellar sources. Detailed analyses of these grains have opened up an amazing new field of astronomy (for recent reviews, see Clayton and Nittler 2004; Lodders and Amari 2005; Lugaro 2005; Meyer and Zinner 2006; Zinner 2004). So far, silicon carbide (SiC), graphite (C), diamond (C), silicon nitride (Si_3N_4), silicates (Messenger et al. 2003; Nguyen and Zinner 2004; Mostefaoui and Hoppe 2004), and oxides, such as corundum (Al_2O_3) or spinel ($MgAl_2O_4$), have been identified as presolar grains. Ion microprobe analyses of individual grains have indeed revealed a variety of isotopic signatures that point toward several stellar sources, such as asymptotic giant branch stars (AGBs) and supernovae (SNe).

Until now, SiC grains have been the most extensively studied. They can be classified into different populations (that is, different stellar birthplaces) on the basis of their C, N, and Si isotopic ratios (see Hoppe and Ott 1997). It is now widely accepted that about 93% of all SiC grains, the so-called mainstream population, are formed in the winds accompanying solar-metallicity AGB stars (Gallino et al. 1993; Lugaro et al. 2003; Ott and Begemann 1990). About 1% correspond to X grains, which are characterized by large excesses of ^{44}Ca (attributed to in situ ^{44}Ti decay) (Amari et al. 1992; Hoppe et al. 2000) and ^{28}Si, fingerprints of type II (i.e., core-collapse) supernovae. In addition, a variety of carbon-rich J-type stars are expected to account for about 4–5% of the overall SiC grains, the so-called A and B grains (with born-again AGB stars, such as the Sakurai's object V4334 Sgr, or other C-rich stellar types, like R or CH stars, not being totally excluded) (Amari et al. 2001a). Other populations include Y (about 1%) and Z grains (about 1%), whose origin is probably linked to low-metallicity AGB stars (Amari et al. 2001b; Hoppe et al. 1997).

A rare variety of SiC grains (<1%) that exhibit a suite of isotopic signatures characteristic of classical nova outbursts, together with a couple of graphite grains, have been reported in the recent years (Amari et al. 2001c; Amari 2002). Details on the isotopic composition of those grains are summarized in Table 1. Since the first studies of dust formation in classical novae (Clayton and Hoyle 1976), all efforts devoted to the identification of potential nova candidate grains relied mainly on the search for low $^{20}Ne/^{22}Ne$ isotopic ratios (with ^{22}Ne attributed to ^{22}Na decay, a signature of a classical nova). In contrast, the nova candidate grains reported by Amari et al. (2001c) and Amari (2002) have been identified on the basis of a handful of different isotopic ratios: the SiC grains have very low $^{12}C/^{13}C$ and $^{14}N/^{15}N$ ratios (much below the typical values reported for X grains), while the graphite grains have low $^{12}C/^{13}C$, but normal $^{14}N/^{15}N$ ratios. However, it has been

Table 1. Presolar grains with an inferred nova origin.

Grain	Composition	$^{12}C/^{13}C$	$^{14}N/^{15}N$	$\delta^{29}Si/^{28}Si$	$\delta^{30}Si/^{28}Si$	$^{26}Al/^{27}Al$	$^{20}Ne/^{22}Ne$
AF15bB-429-3	SiC	9.4 ± 0.2	–	28 ± 30	1118 ± 44	–	–
AF15bC-126-3	SiC	6.8 ± 0.2	5.22 ± 0.11	−105 ± 17	237 ± 20	–	–
KJGM4C-100-3	SiC	5.1 ± 0.1	19.7 ± 0.3	55 ± 5	119 ± 6	0.0114	–
KJGM4C-311-6	SiC	8.4 ± 0.1	13.7 ± 0.1	−4 ± 5	149 ± 6	>0.08	–
KJC-112	SiC	4.0 ± 0.2	6.7 ± 0.3	–	–	–	–
KFC1a-551	C	8.5 ± 0.1	273 ± 8	84 ± 54	761 ± 72	–	–
KFB1a-161	C	3.8 ± 0.1	312 ± 43	−133 ± 81	37 ± 87	–	<0.01
Solar		89	272	0	0	0	14
Nova models		0.2–3	0.1–1900	−950 to1800	−1000 to 47,000	0.01–0.9	0.1–2900

The solar N ratio in the table is that from terrestrial air. Grains AF are from the Acfer 094 meteorite, whereas grains KJ and KF are from the Murchison meteorite (see Amari et al. 2001c and Amari 2002 for details). Errors are 1σ.

Table 2. Presolar SiC grains from Nittler and Hoppe (2005).

Grain	$^{12}C/^{13}C$	$^{14}N/^{15}N$	$\delta^{29}Si/^{28}Si$	$\delta^{30}Si/^{28}Si$	$^{26}Al/^{27}Al$	$\delta^{46}Ti/^{48}Ti$	$\delta^{47}Ti/^{48}Ti$	$\delta^{49}Ti/^{48}Ti$	$\delta^{50}Ti/^{48}Ti$
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	–	–	–	–	–

argued that the original $^{14}N/^{15}N$ ratios of these two graphite grains could have been much lower because there is evidence that indigenous N in presolar graphites can be isotopically equilibrated with terrestrial nitrogen. Indeed, most presolar graphite grains show a large spread in C isotopic ratios but essentially terrestrial N composition (Hoppe et al. 1995). $^{26}Al/^{27}Al$ ratios have been determined only for two of the SiC grains (KJGM4C-100-3 and KJGM4C-311-6) and are very high ($>10^{-2}$). In turn, a determination of the $^{20}Ne/^{22}Ne$ ratio has been inferred only for the graphite grain KFB1a-161 (<0.01). This low $^{20}Ne/^{22}Ne$ ratio suggests that ^{22}Ne likely originated from in situ decay of ^{22}Na (with a mean lifetime τ = 3.75 yr), although the specific value is considerably lower than theoretical predictions for novae. Concerns about the likely nova paternity of these grains have recently been raised (Nittler and Hoppe 2005) on the basis of new measurements performed on three additional micron-sized SiC grains isolated from the Murchison meteorite (see Table 2). These grains have very low $^{12}C/^{13}C$ and $^{14}N/^{15}N$ ratios, similar to the ones reported for the nova candidate grains (Amari et al. 2001c; Amari 2002), but a number of additional imprints suggest that a supernova origin cannot be ruled out.

In this paper, we revisit nova outbursts and discuss whether these explosions constitute a likely stellar birthplace for the sample of grains reported by Amari et al. (2001c), and more recently, by Nittler and Hoppe (2005). Indeed, we will examine some extreme models of nova explosions, evolved at lower initial metallicities or luminosities, for which more violent outbursts are expected, and hence, heavier nucleosynthetic endpoints may be reached. The structure of the paper is as follows: in the Classical Nova Explosions section, we outline the main properties of classical nova outbursts. Their predicted nuclear signatures, in terms of C, N, Ne, Al, and Si isotopic ratios, are discussed in the Predicted Isotopic Ratios in Nova Shells section. A final discussion on the likelihood of a nova paternity for this rare variety of grains will be addressed in the Discussion and Conclusions sections.

CLASSICAL NOVA EXPLOSIONS

Classical novae are fascinating objects that have captivated the interest of astronomers since ancient times. They display a spectacular and extremely fast rise in optical luminosity, reaching peak values of $\sim 10^4$–10^5 $L_\odot$.

The cornerstone for understanding the nature of these events is linked to the observational analysis of old novae (Walker 1954; Kraft 1963). These seminal works have settled the binary nature of a nova, consisting of a large, cool main sequence star that fills its Roche lobe, and a small white dwarf star. Mass transfer through the inner Lagrangian point leads to the formation of an accretion disk that surrounds the compact star. A fraction of this H-rich material ultimately spirals in and ends up on top of the white dwarf, where it accumulates. This forms an accreted envelope in semidegenerate conditions until a thermonuclear runaway (TNR) ensues.

Several hydrodynamic computations of nova outbursts have analyzed the chemical pattern in the ejecta (see Kovetz and Prialnik 1997; Starrfield et al. 1998; and José and Hernanz 1998 and references therein). Due to the high temperatures achieved in the envelope during the TNR, with typical peak values $T_{peak} \sim (2\text{–}3) \times 10^8$ K, novae eject significant amounts of nuclear processed material into the interstellar medium. This has raised the issue of the potential role of classical novae in the Galactic abundances. Typically, 10^{-4}–10^{-5} $M_\odot$ are ejected per nova outburst, contributing to the enrichment of the interstellar medium in a handful of nuclear species, mainly ^{13}C, ^{15}N, ^{17}O, and to some extent, ^{7}Li (CO novae) and ^{26}Al (ONe novae).

This so-called thermonuclear runaway model for the nova outburst (see José et al. 2006 for a recent review) nicely accounts for the gross observational properties that define these events, including the shape of the light curve, the maximum brightness (or luminosity) attained by the star, and the chemical composition of the ejected shells. The nuclear history of the explosion is somewhat recorded in the specific chemical abundance pattern, revealing the characteristic time scale of the TNR as well as the temperatures (and hence the nuclear processes) to which the envelope material has been exposed. Despite several key issues associated with the modeling of the explosion that are not yet fully understood (for instance, the nature of the mixing mechanism that dredges up material from the outermost layers of the white dwarf core into the solar-like accreted envelope, providing the source of metallicity enrichment required to match observations), models account reasonably well for the specific abundance pattern inferred from the ejecta. This includes atomic abundances for a set of elements (cf. H, He, C, O, Ne, Na, etc.), and a plausible nucleosynthetic endpoint around Ca (José and Hernanz 1998; Starrfield et al. 1998).

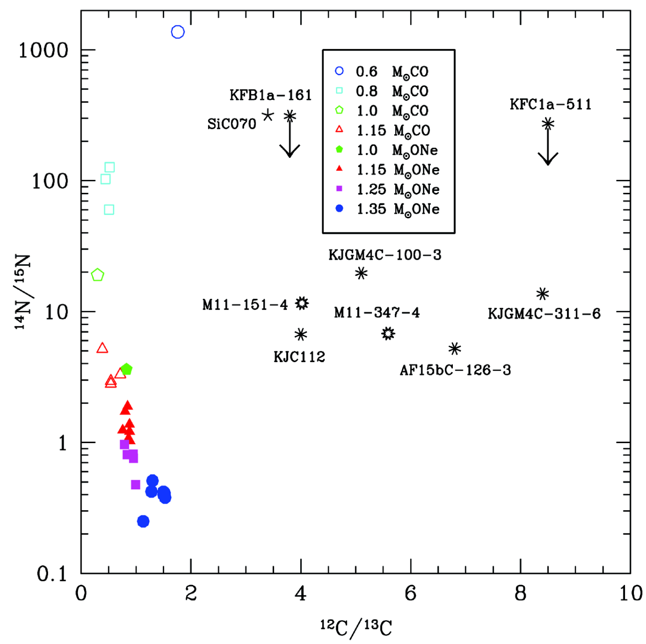

Fig. 1. Nitrogen versus carbon isotopic ratios from a suite of hydrodynamic models of CO and ONe novae (José and Hernanz 1998; Hernanz et al. 1999; José et al. 1999, 2001, 2004). For comparison, data from presolar nova candidate grains (Amari et al. 2001c; Amari 2002; Nittler and Hoppe 2005; Heck et al. 2007), extracted from the Murchison and/or Acfer 094 meteorites, are also shown. Points with arrows represent only upper limits.

PREDICTED ISOTOPIC RATIOS IN NOVA SHELLS

Isotopic abundance ratios for grains of putative nova origin are available for C, N, Ne, Al, Si, and Ti. Here we will focus on their theoretical counterparts, obtained from state-of-the-art hydrodynamic models of the explosion. Calculations have been carried out with the one-dimensional, implicit, Lagrangian, hydrodynamic code SHIVA (see José and Hernanz 1998 for details) that follows the course of the explosion from the onset of accretion up to the expansion and ejection stages.

Carbon

The TNR that powers a classical nova outburst is triggered by the cold CNO reaction $^{12}C(p,\gamma)$, which very efficiently synthesizes huge amounts of ^{13}C in the envelope. This takes place through $^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C$, which in turn leads to a decrease in the final amount of ^{12}C, thus explaining the very low $^{12}C/^{13}C$ ratios (see Fig. 1), ranging from 0.3 to 3 (solar ratio = 89). We conclude that a very low $^{12}C/^{13}C$ ratio represents a clear signature of a classical nova outburst, since low ratios are systematically obtained in all models (CO or ONe), no matter how massive the white dwarf hosting the explosion is.

Nitrogen

In sharp contrast, a much wider range of variation is found regarding the final $^{14}N/^{15}N$ ratios (see also Fig. 1). Whereas explosions involving ONe white dwarfs yield low ratios, around 0.3–4 (for comparison, the terrestrial atmosphere has $^{14}N/^{15}N = 272$; actually, the solar value could well be different) (Owen et al. 2001), CO nova models are characterized by higher ratios, typically around 3–130, but as high as 1900 for extremely light (i.e., 0.6 $M_\odot$ CO) white dwarfs, as a result of the marginal nuclear activity achieved in those models. Since both CO and ONe models start with the same initial ^{14}N content, the different $^{14}N/^{15}N$ ratios reported reflect somewhat different thermal histories during the explosion (in particular, the values of T_{peak}, but also the characteristic time scales of the TNRs). The higher peak temperatures achieved in the ONe models (see José and Hernanz 1998) favor proton-capture reactions on ^{14}N, leading to $^{14}N(p,\gamma)^{15}O(\beta^+)^{15}N$, and are responsible for a higher ^{15}N content in the ejecta and hence a low $^{14}N/^{15}N$ ratio.

It is therefore clear that nova explosions are not characterized by a narrow range of $^{14}N/^{15}N$ ratios, although this can be used as a diagnosis for distinguishing between CO (high $^{14}N/^{15}N$ ratios) and ONe (low $^{14}N/^{15}N$ ratios) novae.

Neon

The $^{20}Ne/^{22}Ne$ isotopic ratio is considered a main fingerprint for the identification of nova grains, with ^{22}Ne coming from ^{22}Na decay. In general, neon isotopic ratios in the ejecta accompanying nova outbursts are deeply influenced by the amount of ^{20}Ne that is dredged up from the outermost

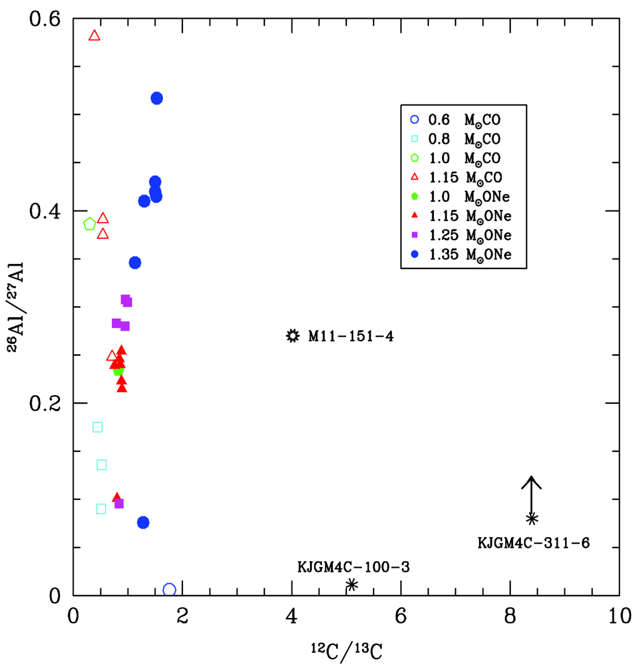

Fig. 2. Same as Fig. 1 for aluminum versus carbon isotopic ratios.

layers of the white dwarf core and ultimately mixed with the solar-like accreted envelope. Hence, neon novae (cf. ONe models) are characterized by large $^{20}Ne/^{22}Ne$ isotopic ratios, typically ranging from 90 to 2900 (solar ratio = 14). In contrast, CO models yield $^{20}Ne/^{22}Ne$ ratios below solar, ranging from 0.1 to 0.7. It is therefore clear that $^{20}Ne/^{22}Ne$ ratios can be used to infer the nature of the underlying white dwarf (cf. CO versus ONe), provided that the specific neon isotopic ratio in the grains corresponds to the original value in the ejected nova shells. However, one has to bear in mind that neon is a noble gas that hardly condenses as a stable compound into a grain (Amari 2002, 2006). Actually, it has been suggested that neon incorporates into grains via implantation, a mechanism not fully understood that can induce large differences between the predicted ratios and those inferred from laboratory analyses of grains.

Aluminum

As pointed out by Ward and Fowler (1980), the synthesis of ^{26}Al requires moderate peak temperatures of the order of $T_{\rm peak} \sim (2–3) \times 10^8$ K and a fast decline from maximum temperatures, conditions which are commonly achieved in nova outbursts. The production of ^{26}Al in nova explosions takes place through proton-capture reactions on ^{25}Mg, which lead to both ^{26}Al ground ($^{26}Al^g$) and short-lived isomeric ($^{26}Al^m$) states. This synthesis mechanism suggests that production of ^{26}Al in novae is very sensitive to the initial composition of the envelope, which depends critically on the nature of the underlying white dwarf. Indeed, it has been shown that ONe novae are more important ^{26}Al producers than CO novae because of the presence of seed "NeNa-MgAl" nuclei (^{25}Mg in particular) in the former.

Production of ^{27}Al in novae is far more complicated. This nucleus is mainly destroyed by proton-capture reactions, whereas several reactions compete in its synthesis: one is $^{26}Mg(p,\gamma)$ (both the initial ^{26}Mg as well as the contribution from $^{26}Al^m$ decay); an alternative path involves $^{27}Si(\beta^+)^{27}Al$, with ^{27}Si coming from proton captures on both $^{26}Al^{g,m}$.

Surprisingly enough, similar $^{26}Al/^{27}Al$ ratios are predicted for both CO and ONe nova models, typically ~0.01–0.9 (Fig. 2). This results from the fact that the initial ^{27}Al abundance in ONe novae is more than two orders of magnitude larger than in CO novae (and more important, is not significantly modified during the course of the TNR). This large ^{27}Al content somewhat compensates the larger synthesis of ^{26}Al in ONe novae.

In contrast to the $^{12}C/^{13}C$ ratio, the typical $^{26}Al/^{27}Al$ ratios associated with novae do not constitute a clear signature of the parent stellar source. In fact, core-collapse supernovae lead to somewhat similar $^{26}Al/^{27}Al$ ratios (for instance, $^{26}Al/^{27}Al$ ranges from ~0.001 in the inner shells of a 25 $M_\odot$ SN II model up to ~0.2 in the He/N-rich shells) (Woosley and Weaver 1995; Meyer et al. 1995). Therefore, we conclude that, in general, the $^{26}Al/^{27}Al$ ratio is neither diagnostic for claiming a nova or supernova origin (except for very high ratios), nor useful for distinguishing between CO and ONe novae (although it can be useful in conjunction with other isotopic ratios).

Silicon

CO novae are characterized by a very limited nuclear activity beyond the CNO mass region. The reason is twofold. First, because of the moderate peak temperatures attained during the explosion, and second, because of the lack of significant amounts of "seed" nuclei above this mass range. Therefore, models of CO novae yield in general close-to-solar Si isotopic ratios in the ejecta (usually expressed as δ values, deviations from solar abundances in permil, $\delta^{29,30}Si/^{28}Si = [(^{29,30}Si/^{28}Si)/(^{29,30}Si/^{28}Si) - 1] \times 1000$).

A quite different pattern is found for ONe models, partially because of the higher peak temperatures achieved in the explosion, but mainly because of the large initial ^{27}Al abundance, a source of ^{28}Si and heavier species. The abundance of ^{28}Si reaches a maximum for the 1.25 $M_\odot$ ONe models. This is due to the fact that, below $T \sim 3 \times 10^8$ K, $^{27}Al(p,\gamma)^{28}Si$, and $^{26}Al^{m,g}(p,\gamma)^{27}Si(p,\gamma)^{28}P(\beta^+)^{28}Si$ dominate over $^{28}Si(p,\gamma)$, but for higher temperatures (achieved only for more massive white dwarf models), destruction of ^{28}Si through proton-capture reactions dominates all ^{28}Si synthesis mechanisms. In contrast, production of both $^{29,30}Si$ increases monotonically with the white dwarf mass: they are synthesized by $^{28}Si(p,\gamma)^{29}P(\beta^+)^{29}Si$ and by

$^{29}Si(p,\gamma)^{30}P(\beta^+)^{30}Si$, respectively, which dominate over the corresponding destruction reactions.

The main consequences of the interplay between the different nuclear processes acting on the Si isotopes (see details in José et al. 2004) is an increase of $\delta^{30}Si/^{28}Si$ with the white dwarf mass (see Fig. 3). Whereas 1.0 $M_{\odot}$ ONe models show a noticeable destruction of ^{30}Si, 1.15 $M_{\odot}$ models yield close-to-solar $\delta^{30}Si/^{28}Si$ values. Excesses of ^{30}Si show up only for white dwarf masses larger than 1.25 $M_{\odot}$, a result of the higher temperatures attained in such models. It is also worth mentioning that, on the other hand, $^{29}Si/^{28}Si$ ratios are usually below solar, and only approach close-to-solar values when the white dwarf mass reaches 1.35 $M_{\odot}$.

DISCUSSION AND CONCLUSIONS

Condensation in O-Rich Environments: Paving the Road to Oxide Grains?

Except for explosions hosting very massive white dwarfs, the C/O ratio in the shells ejected during nova outbursts is almost always below unity. It is, however, generally believed that C > O is required for the formation of SiC or graphite grains. Otherwise, if oxygen is more abundant than carbon, all C is locked up in the very stable CO molecule, and the free O atoms form only oxides and silicates as condensates. Nevertheless, C-rich dust has been observed around several novae (Gehrz et al. 1998; Gehrz 2002 and references therein). Several explanations have been proposed to solve this puzzle. First, equilibrium condensation models have shown that the C/O ratio is not a unique criterion to determine the expected mineralogy in nova shells (see José et al. 2004 for details). Actually, the presence of significant amounts of Al, Ca, Mg, and Si (very common in ONe novae) can dramatically affect the C and O chemistries, leading in some cases to the synthesis of C-rich grains (SiC and graphite) even when C < O. Other studies (Shore and Gehrz 2004) suggest instead that condensation takes place kinetically rather than at equilibrium, dramatically reducing the role of the CO molecule in the expected mineralogy. A final possibility involves variations in the initial C/O ratio in the outer layers of the white dwarf hosting the explosion: it has been shown that if C is slightly more abundant than O in such layers, the subsequent ejected layers become C-rich.

In any case, and because it is easy to drive nova outbursts characterized by O-rich ejecta, one may expect to find nova candidate grains among the oxide population. ^{16}O is by far the most abundant oxygen isotope in both CO and ONe white dwarfs. Hence, the $^{16}O/^{17}O$ and $^{16}O/^{18}O$ ratios in the accreted envelope are initially very high. Different nuclear processes during the TNR, which partially transform ^{16}O into ^{17}O and/or ^{18}O, are responsible for a substantial decrease of these isotopic ratios in the ejecta, whose final values depend strongly on the nova type (i.e., CO or ONe) and on the

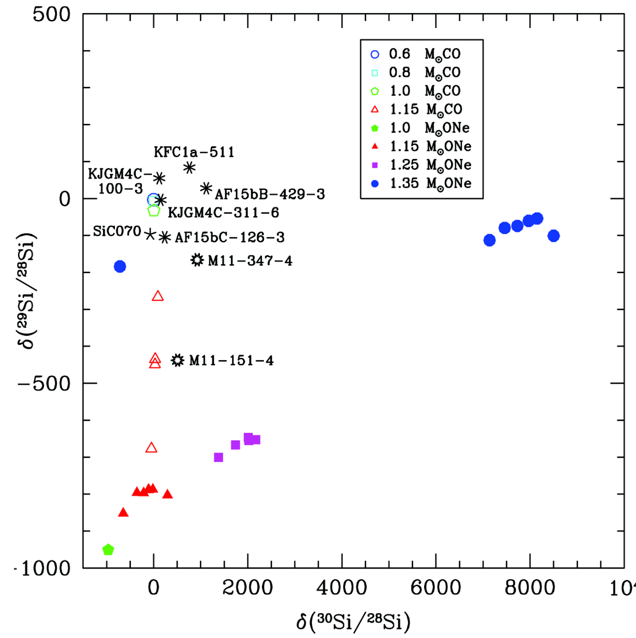

Fig. 3. Same as Fig. 1 for silicon abundances, expressed as delta values (deviations from solar Si ratios in permil; see text for details).

adopted white dwarf mass. In general, CO models are characterized by high $^{16}O/^{18}O$ ratios, ranging from 20 to 39,000 (solar ratio = 499), but moderate $^{16}O/^{17}O$ ratios, ranging from 8 to 230 (solar ratio = 2622). In contrast, ONe models show in general much lower ratios, with $^{16}O/^{18}O$ ratios ranging from 10 to 400, and $^{16}O/^{17}O$ ranging from 1 to 10. The larger white dwarf masses and the larger characteristic time scales of the TNRs in novae hosting ONe white dwarf cores lead to higher peak temperatures than CO models, and therefore to an increase of the nuclear activity. As a consequence, larger amounts of both $^{17,18}O$ are synthesized in ONe novae, which result in much lower $^{16}O/^{17}O$ and $^{16}O/^{18}O$ ratios than models of CO novae. The $^{18}O/^{16}O$ ratios predicted in models of nova outbursts (José et al. 2004) are consistent with the values reported from oxide grains (Nittler et al. 1994, 1998; Lodders and Amari 2005), although some models hosting ONe white dwarfs can actually reach $^{18}O/^{16}O \sim 0.1$. In sharp contrast, the expected $^{17}O/^{16}O$ ratios, ~0.01–1, are in general well above the values reported from oxide grains. The same applies for the expected $^{26}Al/^{27}Al$ ratios. With respect to Mg, nova models yield very low $^{24}Mg/^{25}Mg$ [~0.02–0.3] and low $^{26}Mg/^{25}Mg$ ratios [~0.07–0.2], except for grains condensed in novae hosting low mass CO white dwarfs (cf. 0.6 $M_{\odot}$), for which close-to-solar values are expected (see José et al. 2004). However, it is likely to expect much larger $^{26}Mg/^{25}Mg$ ratios in oxide grains of putative nova origin because of the contribution from $^{26}Al(\beta^+)^{26}Mg$.

Hints of the discovery of putative nova oxide grains have been pointed out recently by Nittler and Hoppe (2005). For instance, the O isotopic ratios inferred for the corundum grain

T54 (Nittler et al. 1997), with $^{16}O/^{17}O \sim 71$ and $^{16}O/^{18}O \sim 2000$, suggest its likely condensation in the nova shells ejected from an outburst on a 0.8 $M_\odot$ CO white dwarf (José et al. 2004). We expect that more oxide grains with a putative nova origin will be identified in the near future.

Stardust from Novae

The isotopic signatures of the nova candidate grains qualitatively agree with current predictions from hydrodynamic nova models. In fact, a detailed comparison between grain data and models suggests that the grains reported by Amari et al. (hereafter A01 grains) may have formed in ONe nova explosions hosting white dwarfs of at least 1.25 $M_\odot$. However, as shown in Figs. 1–3, in order to quantitatively explain the grain data, one has to assume that material newly synthesized in the nova outburst was mixed with more than ten times as much unprocessed, isotopically close-to-solar material before grain formation. It is not clear if the interaction between the ejected shells and the surrounding disk can account for this mixing process.

It is by no means clear if the measurements performed on the three new SiC grains reported by Nittler and Hoppe (2005) (hereafter NH05 grains) can be actually used to infer the paternity of the A01 grains. A close look at Tables 1 and 2 reveals some remarkable differences between the two sets of grains. Hereafter, we will restrict to the SiC fraction of the A01 grains for a fair comparison. Whereas the specific C and N ratios of the two sets are very similar, the NH05 grains show much larger $^{26}Al/^{27}Al$ ratios than the A01 grains. Although ratios of $^{26}Al/^{27}Al \sim 0.3$–0.4 are in principle compatible with nova models, such differences may in fact suggest another parent stellar source. Moreover, the NH05 grains M11-151-4 and M11-334-2 are much more depleted in ^{29}Si ($\delta^{29}Si/^{28}Si \sim -440$ and -490, respectively) than any of the A01 grains (for which $\delta^{29}Si/^{28}Si$ ranges from -105 to $+55$). Furthermore, all SiC grains of the A01 sample, for which $\delta^{30}Si/^{28}Si$ values are available, show a noticeable enhancement in ^{30}Si; in contrast, grain M11-334-2 has a negative $\delta^{30}Si/^{28}Si \sim -490$.

The isotopic differences reported between the two samples make it hard to claim a unique same stellar parent for all the grains (actually, Nittler and Hoppe conclude that grain M11-334-2 is actually an X grain formed in a core-collapse supernova). There are arguments favoring both a nova and a supernova origin (Nittler and Hoppe 2005), and certainly, more multi-element data would be required to disentangle this controversy.

It is worth noting that, in any case, a potential supernova origin is also puzzling, since no single supernova zone (see Woosley and Weaver 1995) is predicted to have ^{30}Si enhancements and simultaneous ^{29}Si depletions as observed in some of these grains. Furthermore, as discussed by Travaglio et al. (1999), no single supernova zone is characterized by very low $^{12}C/^{13}C$ and $^{14}N/^{15}N$ ratios simultaneously, and even after a fine-tuning mixing of different zones, the $^{14}N/^{15}N$ ratios are much too large (even to account for normal X grains). Nevertheless, it has been suggested that inclusion of rotation may drive ^{14}N injection into the He-burning shells of massive stars, leading to a significant increase in the final amounts of ^{15}N, hence decreasing the expected $^{14}N/^{15}N$ ratios (see Langer et al. 1997).

Another SiC grain (240-1) for which a nova origin has been claimed was reported in a recent meeting of the Meteoritical Society (Nittler et al. 2006). Both the $^{12}C/^{13}C$ and $^{14}N/^{15}N$ ratios of grain 240-1 are lower than for any reported presolar grain and consistent with pure nova ejecta with CO white dwarf masses of ~1.0–1.2 $M_\odot$. As the same authors conclude, a supernova origin is unlikely since the non-explosive H burning in such stars cannot produce such low $^{12}C/^{13}C$ ratios. However, the reported ^{29}Si excess ($^{29}Si/^{28}Si > 100$) in such grain is clearly at odds with current theoretical predictions for nova outbursts (José et al. 2004), which yield close-to- or slightly-lower-than-solar $^{29}Si/^{28}Si$ values.

A noble-gas rich grain (SiC070) of a likely nova origin has also been very recently reported by Heck et al. 2007. Although originally classified as a type A+B grain, its C ($^{12}C/^{13}C \sim 3.4$), N ($^{14}N/^{15}N \sim 317$), and Ne (with $^{22}Ne >> ^{20}Ne$) isotopic abundance ratios agree qualitatively with the values predicted for <1 $M_\odot$ CO novae (José et al. 2004).

Titanium from Nova-Like Explosions?

Titanium lies beyond the standard nucleosynthetic endpoint for classical nova outbursts (i.e., Ca). At a first glance, the presence of substantial amounts of titanium (much above solar) in a presolar grain would rule out a nova paternity, no matter how well other isotopic ratios are matched. Of course, the presence of Ti isotopic anomalies in two of the NH05 grains does not necessarily imply that the A01 grains were Ti-rich, although both samples share similarities (and differences as well) in some isotopic ratios. Actually, the specific Ti isotopic pattern in the NH05 grains reveals an unexpected complexity, with no clear trend. One grain, M11-334-2, shows large ^{49}Ti excesses (39% above solar) but close-to-solar $^{46,47,50}Ti$. In sharp contrast, grain M11-151-4 exhibits a deficit in ^{50}Ti (10% below solar, but solar within 1σ error), close-to-solar $^{46,49}Ti$ and ^{47}Ti excesses (22% above solar). In general, X grains attributed to core-collapse supernovae are characterized by large ^{49}Ti excesses and close-to-solar $^{46,47,50}Ti$, matching the pattern described for M11-334-2 but not that corresponding to M11-151-4.

In order to shed light into the controversial origin of these grains, we have performed additional hydrodynamic simulations with the aim to analyze the feasibility of titanium synthesis in novae. This, of course, necessarily implies a more

Table 3. Mean isotopic abundance ratios in the ejecta of models A and B.

Model	$^{12}C/^{13}C$	$^{14}N/^{15}N$	$\delta^{29}Si/^{28}Si$	$\delta^{30}Si/^{28}Si$	$^{26}Al/^{27}Al$	$\delta^{46}Ti/^{48}Ti$	$\delta^{47}Ti/^{48}Ti$	$\delta^{49}Ti/^{48}Ti$
A	2.4	0.21	2310	15,000	0.5	1590	655	1660
B	3.5	0.07	6980	30,800	0.09	10,800	4960	630

violent outburst (see Yaron et al. 2005) in order to overcome the standard nucleosynthetic endpoint achieved in such explosions.

The strength of the explosion is actually determined by the pressure at the base of the envelope (P_{base}) (Fujimoto 1982; MacDonald 1983), which, for a white dwarf of a given mass and radius (M_{wd}, R_{wd}), basically depends on the overall amount of mass piled up in the envelope, ΔM_{env}. Actually, the envelope mass can be increased by decreasing the adopted mass-accretion rate, the initial luminosity of the star, and/or the metallicity of the incoming stream of material from the companion. In the first case, compressional heating is reduced since material accumulates more slowly on top of the white dwarf; as a result, more (cooler) material piles up in semi-degenerate conditions until a TNR ensues. The same applies for lower luminosity (that is, lower central temperature) white dwarfs. Since the triggering reaction for driving a TNR is actually $^{12}C(p,\gamma)$, lower metallicity envelopes will somehow require the accumulation of more material to power the explosion (José et al. 2007).

In this paper we have explored the second possibility by performing two new simulations in which the initial luminosity of the white dwarf, usually assumed to be $\sim 10^{-2}$ $L_\odot$, has been decreased arbitrarily by factors of 3 (model A) and 10 (model B), respectively (that is, $L_{wd} = 3.3 \times 10^{-3}$ $L_\odot$ and 10^{-3} $L_\odot$). These values correspond to cooler white dwarfs that have experienced longer cooling times before mass-transfer from the companion star ensues. Actually, it is expected that such low luminosities could be reached by some cataclysmic binary systems (Sion 1999).

The violent TNRs obtained in models A and B are now capable of bypassing Ca, extending the nuclear activity several mass units beyond (Table 3). Indeed, model A shows large $^{46,49}Ti$ excesses and somewhat lower amounts of ^{47}Ti, whereas model B yields large $^{46,47}Ti$ excesses and moderate amounts of ^{49}Ti. Both models are characterized by huge ^{30}Si excesses in all the ejected shells, whereas ^{29}Si is much above solar in the innermost layers but depleted in the most external ones. The fact that $\delta^{30}Si/^{28}Si$ is always >0 seems to rule out classical novae as the likely parent source of grain M11-334-2. This conclusion is corroborated by the 50% excess in ^{44}Ca (attributed to in situ decay of ^{44}Ti) measured in this grain, hence supporting a supernova origin. With respect to M11-151-4, we cannot discard at this stage that an extreme nova may account for its specific abundance pattern, although the initial luminosities required seem a bit too extreme for such events. Clearly, more simulations exploring in detail the parameter space are required to answer the question.

All in all, we conclude that the origin of the A01 and NH05 grains probably involves more than one progenitor, with classical novae being likely birthplaces for most of the A01 grains. Somewhat extreme explosions may actually account for some of the NH05 grains, although evidences suggest that at least grain M11-334-2 was actually made in a core-collapse supernova (Nittler and Hoppe 2005). An additional conclusion of this study is the need for a simultaneous measurements for several elements in order to better constrain the origin of presolar nova grain candidates, since some isotopic ratios are, at least qualitatively, consistent with both a supernova and a nova origin.

Much remains to be done in our understanding of nova explosions (see a detailed discussion in José and Shore 2007), and certainly laboratory analyses of presolar stardust will become a powerful method to constrain our theoretical predictions. We are still facing a problem of statistics, with only a handful of grains tentatively attributed to nova-like explosions. New devices, such as the NanoSIMS, are expected to play a major role in the search for new grains of putative nova origin. But here again, new unexpected surprises will show up. In fact, the improved spatial resolution and sensitivity of the NanoSIMS have already allowed to measure abundance gradients inside some grains (in particular, in certain graphite spherules). Ernst Zinner has certainly been a major player in this amazing story since the beginning, and we hope that he will continue unveiling the mysteries of presolar grains for another seventy years.

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