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Constraining Models of Classical Nova Outbursts with the Murchison Meteorite

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Abstract: Infrared observations of nova light curves reveal that classical novae form grains in the expanding shells, ejected into the interstellar medium as a consequence of a violent outburst. Such grains contain nucleosynthetic fingerprints of the nova explosion. In this paper, we analyse different isotopic signatures expected to be present in nova grains on the basis of detailed hydrodynamic calculations of CO and ONe novae and compare them with recent determinations of presolar nova grains from the Acfer 094 and Murchison meteorites.

Keywords: novae, cataclysmic variables — nucleosynthesis, abundances, isotopic anomalies, dust — meteors

1 Introduction

Classical novae are fascinating objects, at the crossroads of nuclear physics, stellar astrophysics and cosmochemistry. They are powered by rather violent thermonuclear runaways (TNRs) that take place on the white dwarf (WD) components of close binary systems (see Kovetz & Prialnik 1997; José & Hernanz 1998; Starrfield et al. 1998, 2000, and references therein). Typically 10^{-4}–10^{-5} $M_\odot$ are ejected per outburst, contributing to the enrichment of the interstellar medium with a variety of nuclear species, mainly ^{13}C, ^{15}N and ^{17}O, plus traces of other isotopes such as ^{7}Li, ^{20}Ne, ^{26}Al and ^{28}Si. This is a direct consequence of the high peak temperatures achieved in the course of the explosion that induce significant nuclear processing in the accreted envelope.

This so-called *thermonuclear runaway model* nicely accounts for the *gross* observational properties of nova outbursts, including the light curve, the maximum magnitude attained by the star and the chemical composition of the ejected shells. It is somewhat surprising that despite the problems associated with the modelling of the explosion (essentially, the unknown mechanism responsible for the mixing of the solar-like accreted matter and the CO- or ONe-rich material from the outermost white dwarf layers, as well as the overall amount of matter ejected by the explosion; see details in Starrfield 2002), there is an excellent agreement between theory and observations with regard to nucleosynthesis. This agreement includes the atomic abundances of H, He, C, O, Ne and Na-Fe, inferred from observations of the ejecta, and a plausible endpoint for nova nucleosynthesis around Ca (José & Hernanz 1998; Starrfield et al. 1998).

Because the nuclear path is very sensitive to the thermal history of the envelope, limits can be imposed on several properties associated with the explosion (peak temperatures, characteristic timescales and so forth), thereby helping to constrain the models. However, a direct comparison of model predictions with the elemental abundance pattern inferred from observations of nova ejecta relies only on atomic abundances and so does not impose very strict limits on these models. In contrast, a much more precise set of constraints may be obtained if information on specific isotopic abundances were available. Such detailed information can, in principle, be achieved through isotopic analysis of presolar grains in the laboratory.

In the past, the identification of presolar nova grains from meteorites relied only on low ^{20}Ne/^{22}Ne ratios (with ^{22}Ne being attributed to ^{22}Na decay; see Amari et al. 1995; Nichols et al. 2003), but recently five SiC and two graphite grains that exhibit several isotopic signatures characteristic of nova nucleosynthesis have been isolated from the Acfer and Murchison meteorites (Amari et al. 2001; Amari 2002). This discovery provides valuable constraints on models of nova nucleosynthesis and offers interesting possibilities for future studies.

In this paper we compare the information extracted from such grains with the theoretical yields obtained from recent numerical calculations of nova outbursts (José & Hernanz 1998; Hernanz et al. 1999; José et al. 1999, 2001 and unpublished data). These calculations were carried out with the one-dimensional, implicit, lagrangian, hydrodynamic code *SHIVA* (see José & Hernanz 1998 for details) that follows the course of the explosion from the onset of accretion up to the expansion and ejection stages.

2 Theoretical Isotopic Ratios in Nova Ejecta

2.1 Nitrogen and Carbon Isotopic Ratios

A wide range of variation in the final ^{14}N/^{15}N ratios is found in the shells ejected during a nova outburst (see Fig. 1). Explosions involving ONe white dwarfs yield low

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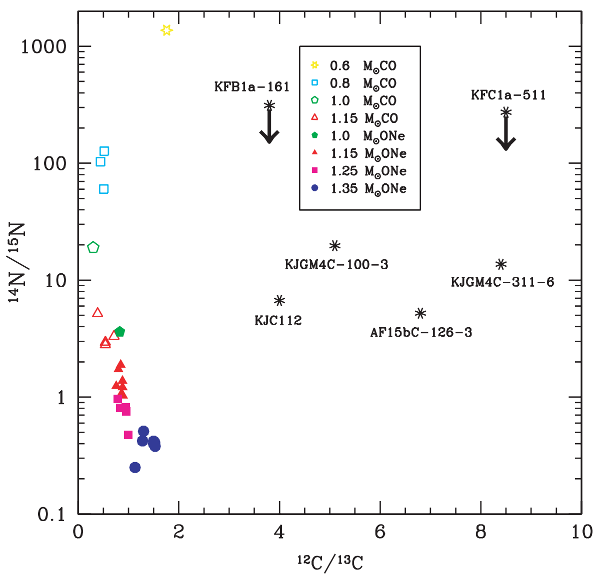

Figure 1 Nitrogen versus carbon isotopic ratios, obtained from a series of hydrodynamic models for both CO and ONe novae (José & Hernanz 1998; Hernanz et al. 1999; José et al. 1999, 2001; and unpublished data). Data from presolar nova grains isolated from the Acfer 094 and Murchison meteorites (Amari et al. 2001; Amari 2002) are also shown.

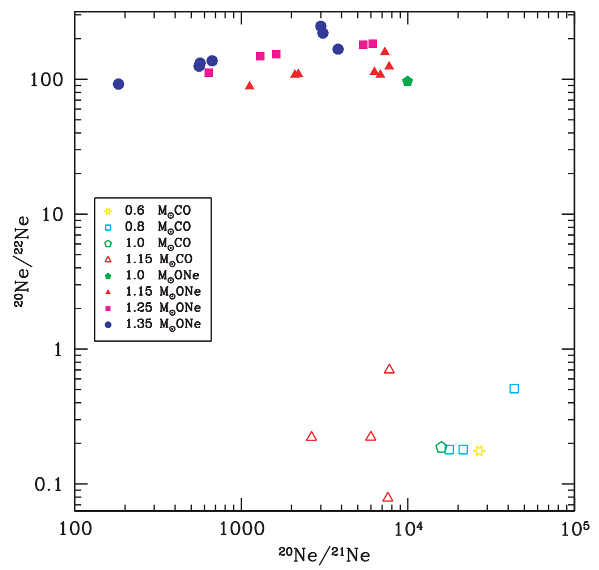

Figure 2 Same as Fig. 1, for the ^{20}Ne/^{21}Ne and ^{20}Ne/^{22}Ne isotopic ratios. An upper limit of ^{20}Ne/^{22}Ne < 0.01 has been determined for graphite grain KFC1a-161 (see Nichols et al. 2003).

ratios of about 0.3–4 (solar ratio = 272), whereas CO nova models are characterised by higher ratios, typically about 3–130. Ratios can be as high as ∼1400 for the extreme 0.6 $M_\odot$ CO case, a result of the marginal nuclear activity found in this low-mass CO model, a model which is characterised by final isotopic ratios that are close to the initial ones for a large number of species.

The differences reported in the final N ratios between CO and ONe models reflect differences in the main nuclear paths attained in the course of the explosions. The synthesis of ^{15}N depends critically on the amount of ^{14}N available. Since both models start with the same initial ^{14}N content, differences in the ejecta reflect different thermal histories during the explosion (in particular, differences in $T_{\rm peak}$). The higher peak temperatures achieved in the ONe models (see José & Hernanz 1998) favour proton-capture reactions onto ^{14}N, leading to ^{14}N(p,γ)^{15}O(β^+)^{15}N and are thereby responsible for a higher ^{15}N content in the ejecta. This fact suggests that the ^{14}N/^{15}N ratio can be used for distinguishing between CO and ONe novae: large ratios, of the order of 100–1000, can only be achieved in explosions involving low-mass CO novae.

In contrast to the N isotopic ratios, both CO and ONe models yield very low ^{12}C/^{13}C ratios (see Fig. 1), in the range ∼0.3–1.8 (solar ratio = 89). Such low ratios result from a very efficient synthesis of ^{13}C through ^{12}C(p,γ)^{13}N(β^+)^{13}C which, in turn, leads to a decrease in the final amount of ^{12}C.

2.2 Oxygen and Neon Isotopic Ratios

Oxygen isotopic ratios in nova ejecta depend on the nova type (namely, CO or ONe) and on the white dwarf mass ($M_{\rm wd}$). In general, CO models are characterised by high ^{16}O/^{18}O ratios, ranging from 20 to 39 000 (solar ratio = 499), but moderate ^{16}O/^{17}O ratios, from 8 to 230 (solar ratio = 2 622). In contrast, lower ratios are, in general, found for ONe models: whereas ^{16}O/^{18}O ranges from 10 to 400, ^{16}O/^{17}O ranges from 1 to 10.

Because oxygen in the white dwarf is almost pure ^{16}O in both CO and ONe models, the initial oxygen isotopic ratios are extremely high. The decrease from such huge values down to the ones predicted for the ejecta is the result of the nuclear processes that transform ^{16}O to ^{17,18}O, beginning with proton captures onto ^{16}O, which require high enough temperatures to overcome the Coulomb barrier. Indeed, at the typical temperatures achieved during nova outbursts, ^{16}O always decreases, since ^{16}O(p,γ) dominates over ^{15}N(p,γ)^{16}O, ^{19}F(p,α)^{16}O, and ^{17}F(γ,p)^{16}O. ^{17}O is synthesised by ^{16}O(p,γ)^{17}F(β^+)^{17}O, and can be destroyed either by ^{17}O(p,γ)^{18}F (^{18}F decays into ^{18}O) or by ^{17}O(p,α)^{14}N. The dominant destruction reaction for ^{18}O is ^{18}O(p,α). ONe models, which involve more massive white dwarfs and so reach higher temperatures than CO models, yield larger amounts of both ^{17,18}O, and thus lower ^{16}O/^{17}O and ^{16}O/^{18}O ratios, than models of CO novae.

Other interesting sources of information are the Ne isotopic ratios, which may provide a criterion for distinguishing between CO and ONe novae: the higher initial ^{20}Ne content in ONe novae is the main reason for their having much higher ^{20}Ne/^{22}Ne ratios (Fig. 2), ranging typically from about 90 to 250 (solar ratio = 14). In contrast, CO models yield ^{20}Ne/^{22}Ne ratios ranging only from about 0.1 to 0.7.

In their ^{20}Ne/^{21}Ne ratios, differences between CO and ONe novae are not as extreme (see Fig. 2) and ratios for the two models overlap at values of 2500–10 000. Moreover, some models with very massive white dwarfs (that is, 1.35 $M_\odot$ ONe) exhibit moderate ^{20}Ne/^{21}Ne ratios, around

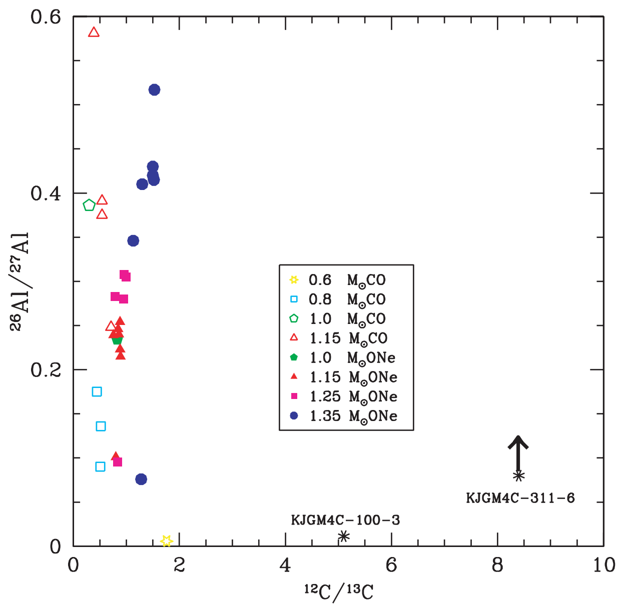

Figure 3 Same as Fig. 1, for aluminium versus carbon isotopic ratios.

500 for the most representative case, whereas very low-mass CO WD models are characterised by extremely large ^{20}Ne/^{21}Ne ratios, ranging from 18 000 to 44 000. Such huge ratios reflect the fact that in most nova models ^{20}Ne is scarcely modified during the course of the explosion as its destruction by proton-capture reactions requires rather high temperatures. In contrast, ^{21}Ne, a fragile isotope, is almost completely destroyed by proton-capture reactions. In addition, as the temperature rises, the synthesis path through ^{20}Ne(p,γ)^{21}Na(β^+)^{21}Ne is halted as soon as proton capture onto ^{21}Na becomes faster than its β^+-decay.

2.3 *Aluminium and Magnesium Isotopic Ratios*

Similar ^{26}Al/^{27}Al ratios (typically ~0.01–0.6, see Fig. 3) are obtained for both CO and ONe nova models. Although ^{26}Al is synthesised efficiently only in ONe novae, the fact that the initial ^{27}Al abundance in such novae exceeds that in CO novae by more than two orders of magnitude (and is not strongly modified during the explosion) results in similar ratios in the two nova types. Therefore, the ^{26}Al/^{27}Al ratio is not useful for distinguishing between CO and ONe novae.

The only way to synthesise the long-lived ^{26}Al isotope (that is, the ground state) in nova explosions is through proton-capture reactions onto ^{25}Mg, which can produce both the ^{26}Al ground (^{26}Al^g) and isomeric (^{26}Al^m) states. The synthesis of ^{27}Al is a bit more complicated. Whereas ^{27}Al is mainly destroyed by ^{27}Al(p,γ), several reactions compete in its synthesis. One is ^{26}Mg(p,γ) (with ^{26}Mg coming from its initial abundance as well as from ^{26}Al^m-decay). Another is ^{27}Si(β^+)^{27}Al, with ^{27}Si coming from proton captures onto both isomers ^{26}Al^{g,m}.

Both CO and ONe nova models yield low ^{24}Mg/^{25}Mg (~0.02–0.3) and ^{26}Mg/^{25}Mg (~0.07–0.2) ratios. Again, the extreme 0.6 M$_\odot$ CO case is an exception, yielding larger ratios of ^{24}Mg/^{25}Mg = 4.3 and ^{26}Mg/^{25}Mg = 0.7.

The CO nova models show a rather complicated pattern because Mg synthesis is very sensitive to the maximum temperature (and thus to the adopted white dwarf mass) attained in the envelope. Since proton captures onto ^{26}Mg require high enough temperatures to overcome its Coulomb barrier, the final ^{26}Mg abundances are, in general, very close to the initial ones (with only a small decrease for the 1.15 M$_\odot$ CO case). The 0.6 M$_\odot$ CO model shows no nuclear activity involving ^{24}Mg, but at 0.8 M$_\odot$ the CO model begins to show a decrease in the final ^{24}Mg yield, since at the moderate temperatures reached in this model ^{24}Mg(p,γ)^{25}Al dominates ^{23}Na(p,γ)^{24}Mg, which in turn explains the increase in ^{25}Mg powered by ^{25}Al(β^+)^{25}Mg. However, when the temperature reaches $\sim 2 \times 10^8$ K (as in the 1.15 M$_\odot$ CO models), the ^{24}Mg(p,γ)^{25}Al and ^{23}Na(p,γ)^{24}Mg rates become comparable, halting the decrease in the final ^{24}Mg yield. At the same time, ^{25}Mg(p,γ) dominates over ^{24}Mg(p,γ)^{25}Al(β^+)^{25}Mg, which accounts for a decrease in the ^{25}Mg yield.

In contrast, for the ONe models, the final Mg yields do not depend much on the white dwarf mass: in all models, both the final ^{24,26}Mg abundances are significantly lower (by two and one orders of magnitude, respectively) than the initial values, whereas ^{25}Mg decreases by only a factor of about 2. Most of the destruction of Mg isotopes takes place at temperatures around 2×10^8 K (see José et al. 1999). The differences with respect to the results for CO models are essentially due to significant differences in the initial chemical composition (the ONe models are, for instance, much richer in ^{23}Na and ^{25,26}Mg), which affect not only the nuclear path, but also the characteristic timescales of the explosion and thus the exposure time to proton-capture reactions.

2.4 *Silicon Isotopic Ratios*

CO novae show only very limited nuclear activity beyond the CNO mass region because of the moderate peak temperatures attained during the explosion and also because of the lack of significant amounts of 'seed' nuclei above this mass range. Therefore, as shown in Fig. 4, hydrodynamic models of CO novae yield, in general, close-to-solar Si isotopic ratios in the ejecta, ratios that are usually expressed as δ values (deviations from solar abundances in permil), where

$$\delta^{29,30}\mathrm{Si}/^{28}\mathrm{Si} = \left[\frac{(^{29,30}\mathrm{Si}/^{28}\mathrm{Si})}{(^{29,30}\mathrm{Si}/^{28}\mathrm{Si})_\odot} - 1 \right] \times 1000 \qquad (1)$$

A quite different pattern is found for ONe models, partially because of the higher peak temperatures achieved in the explosion, but also because of the higher initial ^{27}Al abundance—a source of ^{28}Si and heavier 'seed' nuclei. The abundance of ^{28}Si increases as the white dwarf mass increases from 1 M$_\odot$ to 1.25 M$_\odot$ in ONe models and decreases slightly for 1.35 M$_\odot$ models. This results from the fact that at temperatures below $\sim 3 \times 10^8$ K, ^{27}Al(p,γ)^{28}Si and/or ^{26}Al^{m,g}(p,γ)^{27}Si(p,γ)^{28}P(β^+)^{28}Si

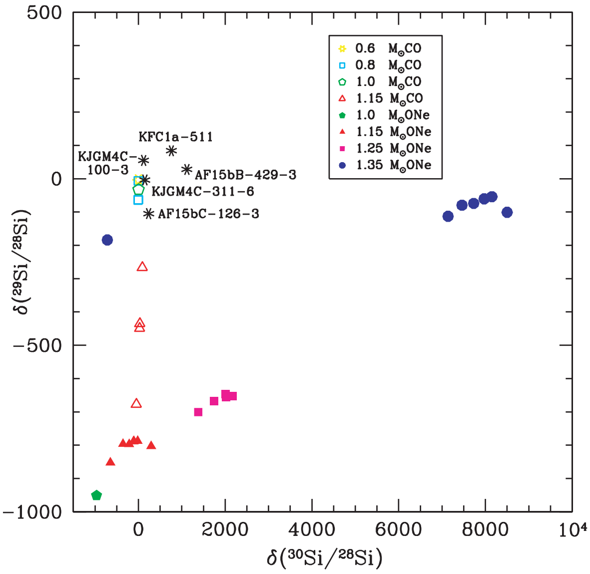

Figure 4 Same as Fig. 1, for silicon isotopic ratios, expressed as delta values (deviations from the solar Si isotopic ratios in permil).

dominate over ^{28}Si(p,γ), but for higher temperatures destruction of ^{28}Si through proton-capture reactions dominates all ^{28}Si synthesis reactions.

In contrast, both ^{29,30}Si increase monotonically with the white dwarf mass. They are synthesised by ^{28}Si(p,γ)^{29}P(β^+)^{29}Si and by ^{29}Si(p,γ)^{30}P(β^+)^{30}Si, which dominate destruction through proton-capture reactions. Fig. 4 shows a clear increase in δ^{30}Si/^{28}Si with increasing white dwarf mass: whereas 1.0 $M_\odot$ ONe models show noticeable destruction of ^{30}Si, 1.15 $M_\odot$ ONe models yield close-to-solar ^{30}Si/^{28}Si ratios. Excesses appear for $M_{\rm wd} \geq 1.25\,M_\odot$, a result of the higher temperatures attained in such models. On the other hand, ^{29}Si/^{28}Si ratios are below solar and only approach close-to-solar values when the white dwarf mass reaches 1.35 $M_\odot$.

3 Comparison with Other Calculations

We compared our theoretical predictions with recent results obtained from similar hydrodynamic models of nova outbursts by Kovetz & Prialnik (1997) and Starrfield, Gehrz & Truran (1997) for CO novae and by Starrfield et al. (1998, 2000) for ONe novae. In general, there is good agreement with the calculations reported by Kovetz & Prialnik (1997) and by Starrfield et al. (1998) for novae hosting CO white dwarf cores, in particular for ^{12}C/^{13}C and ^{16}O/^{17}O ratios. One discrepancy involves the range of ^{14}N/^{15}N ratios predicted for nova outbursts. The high ^{14}N/^{15}N ratios reported by Kovetz & Prialnik (1997) and Starrfield et al. (1997) are obtained in explosions that achieve very low peak temperatures (those involving low-mass white dwarfs) for which ^{14}N(p,γ)^{15}O(β^+)^{15}N is not very efficient, thus reducing the ^{15}N content and increasing the final ^{14}N/^{15}N ratio. This interpretation is fully consistent with the results presented in this paper for the 0.6 $M_\odot$ CO white dwarf model, which achieves the highest N ratio. Differences in the adopted reaction rates, opacities, equations of state and input parameters such as the mass-accretion rate could be responsible for the remaining differences.

For ONe models there is also excellent agreement with the calculations reported by Starrfield et al. (1998, 2000) for many isotopic ratios, including ^{12}C/^{13}C, ^{26}Al/^{27}Al and the Si isotopic ratios. We stress that, besides the expected differences attributable to the specific choice of input physics, the main source of differences between ONe models is probably the specific prescription adopted for the initial amounts of O, Ne and Mg in the outer shells of the white dwarf, where mixing with the solar-like accreted material takes place. Whereas the calculations by Starrfield et al. (1998, 2000) assume a core composition based on hydrostatic models of carbon-burning nucleosynthesis by Arnett & Truran (1969) that has a high ^{24}Mg abundance (with ^{16}O:^{20}Ne:^{24}Mg $\simeq$ 1.5:2.5:1), we use a more recent prescription taken from stellar evolution calculations of intermediate-mass stars, for which the ^{24}Mg content is much lower (^{16}O:^{20}Ne:^{24}Mg = 10:6:1) (Ritossa, García–Berro & Iben 1996). Calculations based on this new ONe white dwarf composition (José & Hernanz 1998, José et al. 1999) suggest, for instance, that the contribution of novae to the Galactic ^{26}Al abundance is small, in good agreement with the results derived from the COMPTEL map of the 1809 keV ^{26}Al emission in the Galaxy (see Diehl et al. 1995) which points towards young progenitors (type II supernovae and Wolf–Rayet stars) without, however, excluding some contribution from other sources such as classical novae.

4 Comparison with Isotopic Analysis of Presolar Grains from the Acfer 094 and Murchison Meteorites

A small fraction of SiC and graphite grains isolated from samples of the Acfer 094 and Murchison meteorites carry isotopic signatures that indicate that these grains have an origin in nova explosions. The SiC grains have very low ^{12}C/^{13}C and ^{14}N/^{15}N ratios, while the graphite grains have low ^{12}C/^{13}C but normal ^{14}N/^{15}N ratios. However, the original ^{14}N/^{15}N ratios of these two graphite grains could have been much lower, since there is evidence that indigenous N in presolar graphites has been isotopically equilibrated. For example, most presolar graphite grains show a huge range in C isotopic ratios but essentially normal N (Hoppe et al. 1995). Recent isotopic imaging of C and O inside slices of graphite spherules showed gradients from highly anomalous ratios in the centre to more normal ratios close to the surface, also indicating isotopic equilibration (Stadermann et al. 2002). The C and N ratios determined in nova grains are well below the values found for mainstream grains, as well as for all other types of presolar SiC grains (see fig. 1 in Amari et al. 2001). The N ratios fall well within the limits shown by Figure 1 for N isotopic ratios obtained in hydrodynamic calculations of nova outbursts. The C isotopic ratios are, however, a bit larger than those obtained in models of the explosion.

^{26}Al/^{27}Al ratios have been determined for only two SiC grains with an inferred nova origin and are very high

($>10^{-2}$; see Amari et al. 2001), higher than the ratios determined for other types of presolar SiC grains except grains with a supernova origin. The lower limit determined for the SiC candidate grain KJGM4C-311-6, 0.08, is compatible with the values obtained for some massive ONe models. However, the ratio of 0.01 measured in the other SiC grain KJGM4C-100-3 appears slightly too low for current theoretical models of ONe novae.

We note that the ^{20}Ne/^{22}Ne ratio of graphite grain KFC1a-161 (<0.01; ^{22}Na/C $= 9 \times 10^{-6}$; see Nichols et al. 2003) is considerably lower than the ratios predicted by nova models (see Section 2). Usually, neon is incorporated into grains via implantation, since noble gases do not condense as stable compounds into grains (Amari 2002). However, the low ^{20}Ne/^{22}Ne ratio measured in this grain suggests that the ^{22}Ne has not been implanted in the ejecta, but most likely originated from decay of ^{22}Na ($\tau = 3.75$ yr) inside the grain.

Silicon isotopic ratios of the five SiC grains of putative nova origin are characterised by ^{30}Si excesses and close-to- or slightly lower-than-solar ^{29}Si/^{28}Si ratios. Whereas CO nova models (Kovetz & Prialnik 1997; Starrfield et al. 1997; José & Hernanz 1998; Hernanz et al. 1999) predict close-to-solar ^{30}Si/^{28}Si and close-to- or lower-than-solar ^{29}Si/^{28}Si ratios, ONe nova models predict huge enrichments of ^{30}Si and close-to or lower-than-solar ^{29}Si/^{28}Si ratios (José & Hernanz 1998; Hernanz et al. 1999; José, Coc, & Hernanz 1999, 2001; Starrfield et al. 1998, 2000).

The isotopic signatures of these grains qualitatively agree with current predictions from hydrodynamic models of nova outbursts. In fact, a comparison between grain data and nova models suggests that these grains likely formed in ONe novae with a white dwarf mass of at least 1.25 $M_\odot$ (Amari et al. 2001). However, in order to quantitatively explain the grain data, one has to assume that material newly synthesised in the nova outburst was mixed with more than ten times as much unprocessed, isotopically close-to-solar, material before grain formation.

It is also important to stress that condensation of SiC (and graphite) grains in a gas with O > C, usually encountered in nova ejecta (see spectroscopic determinations in Starrfield et al. 1998, Table 1, and in Gehrz, Truran & Williams 1998, Table 2), is far from being understood. Although equilibrium condensation requires C > O for the formation of SiC and/or graphite grains (the reason being that the formation of the CO molecule, which drives the condensation process, does not leave any free C if O > C), C-rich dust has been detected around some novae (Gehrz et al. 1993; Starrfield et al. 1997). A recent explanation (Evans 2002; Gehrz 2002) relies on the hypothesis that the formation of the CO molecule does not go to completion, thus leaving some free C for the simultaneous formation of carbonaceous grains (SiC, C and so on) in the same ejected shells.

From the analysis of theoretically predicted isotopic ratios in nova ejecta and their relationship with laboratory measurements on samples of the Acfer 094 and Murchison meteorites, we can conclude that nova grains are characterised by low C ratios, high Al ratios and close-to- or slightly lower-than-solar ^{29}Si/^{28}Si ratios. Other predicted isotopic ratios depend on the nova type: for instance, we may expect that grains condensed in the ejecta from massive ONe novae would exhibit significant ^{30}Si excesses, whereas those from explosions in CO novae would show close-to-solar ^{30}Si/^{28}Si ratios. Predictions of N and Ne isotopic ratios in the grains are difficult because of the above-mentioned problems related to N isotopic equilibration and because ^{22}Ne could come from ^{22}Ne implantation or from decay of ^{22}Na. Furthermore, predicted N ratios show an extreme dispersion, ranging from values around 0.3 up to more than 1000. Presolar oxide grains are much rarer than SiC or graphite grains and no oxide grains with a nova signature have been discovered to date. They would be clearly identified by huge ^{17}O and somewhat smaller ^{18}O excesses. Finally, Al-Mg spinel grains may show significant excesses in both ^{25,26}Mg.

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