Pre-solar grains from supernovae and novae

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Abstract. Pre-solar grains from supernova ejecta – silicon carbide of type X, Si_3N_4 and low-density graphite – are characterized by Si isotopic anomalies (mainly ^{28}Si excesses), low $^{14}N/^{15}N$, high $^{26}Al/^{27}Al$ ratios, and occasionally by excesses in ^{44}Ca (from ^{44}Ti decay). Overall isotopic features of these SiC and graphite grains can be explained by mixing of inner Si-rich zones and the outer C-and He-rich zones, but supernova models require fine tuning to account for $^{14}N/^{15}N$ and $^{29}Si/^{28}Si$ ratios of the grains. Isotopic ratios of Zr, Mo and Ba in SiC X grains may be explained by a neutron burst model. Some of the pre-solar nanodiamonds require a supernova origin to explain measured xenon isotopic ratios. Only a few nova grain candidates, with low $^{12}C/^{13}C$, $^{14}N/^{15}N$, and high $^{26}Al/^{27}Al$ ratios, have been identified.

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1. Introduction

Since the recovery of the first pre-solar grains in 1987 a considerable amount of data has been accumulated in this new field of astronomy. Pre-solar minerals currently known include nanodiamond (Lewis *et al.* 1987), SiC (Bernatowicz *et al.* 1987; Tang & Anders 1988), graphite (Amari *et al.* 1990), Al-bearing oxides (Hutcheon *et al.* 1994; Nittler *et al.* 1994), Si_3N_4 (Nittler *et al.* 1995), silicates (Messenger *et al.* 2003; Nguyen & Zinner 2004; Nagashima, Krot & Yurimoto 2004), and refractory inclusions inside graphite (Bernatowicz *et al.* 1991) and SiC grains (Bernatowicz, Amari & Lewis 1992). Isotopic analyses on individual grains by secondary ion mass spectrometry indicate that a small fraction of pre-solar grains originated in supernovae (e.g., Amari & Zinner 1997). There is a handful of grains that show characteristics of novae (Amari *et al.* 2001; Nittler & Hoppe 2005). This paper summarizes information on pre-solar grains of supernova and of probable nova origins. More information can be found in several review papers (Zinner 1998; Clayton & Nittler 2004; Lodders & Amari 2005) and references therein.

2. Pre-solar grains from type II supernovae

2.1. *Oxides, SiC type X, Si_3N_4 and low-density graphite*

The major dust forming elements (e.g., Al, Ca, Mg, Si) are mainly produced and ejected by core-collapse type II supernovae (SNe) and if they condense from supernova (SN) ejecta, there should be abundant grains from SNe among pre-solar grains. However, only a few oxide grains and one olivine aggregate of probable SN origin have been identified (Choi *et al.* 1998; Nittler *et al.* 1998; Messenger, Keller & Lauretta 2005). They show either ^{16}O or ^{18}O excesses (here and elsewhere, an excess is relative to 'normal' isotopic composition). It is odd that SN oxide grains are so rare because ^{16}O is the third most abundant isotope ejected from SNe and overall SN ejecta have C/O < 1, so there should be many more SN oxide grains. One explanation could be that SN oxide grains are

too small ($\ll 0.1\,\mu$m) to survive for long in the ISM. Such small oxide grains are also unrecoverable from meteorites during chemical pre-solar grain separation procedures.

Strangely, most of the known pre-solar grains from SNe are dominantly carbonaceous: the type X SiC (Amari *et al.* 1992; Hoppe *et al.* 2000) and Si_3N_4 (Nittler *et al.* 1995), and the low-density graphite (Amari, Zinner & Lewis 1995; Travaglio *et al.* 1999) grains. However, only about 1 % of carbonaceous pre-solar grains originated from SNe.

The carbonaceous SN grains are characterized by ^{28}Si excesses (but a few graphite grains show ^{29}Si and/or ^{30}Si excesses), lower ^{14}N/^{15}N ratios than that of air (272), and typically isotopically light C, although their ^{12}C/^{13}C ratios range from 3.4 to 7200 (solar: 89). Many graphite grains show ^{18}O excesses (^{18}O/^{16}O up to 185×solar). Type II supernovae are the main producers of ^{28}Si so excesses of this isotope indicate a SN origin of these grains. Definite proof of their SN origin are excesses in ^{44}Ca from decay of ^{44}Ti ($T_{1/2} = 60$ a) which must have been incorporated when the SiC type X and low-density graphite grains formed (Hoppe *et al.* 1996; Nittler *et al.* 1996). Since ^{44}Ti is produced only in explosive nucleosynthesis, the initial presence of ^{44}Ti in the grains proves supernova origin of these grains. Supernova grains also once contained radioactive ^{26}Al and ^{41}Ca, which are traceable by excesses in their decay products ^{26}Mg and ^{41}K. The initial ^{26}Al/^{27}Al ratios range up to 0.6 in SN grains.

The measured isotopic compositions of the SiC and graphite grains require mixing of different compositional SN zones. For example, high ^{26}Al/^{27}Al ratios require contributions from the He-N zone (where the CNO cycle takes place), and high ^{18}O/^{16}O ratios in low-density graphite grains need contributions from the He-C zone (where the triple α reaction operates). The He-N and He-C zones have to be mixed to account for the observed range of ^{12}C/^{13}C ratios, and the innermost Si-rich zones must contribute e.g., ^{28}Si, and ^{44}Ti. Mixing must also achieve C/O > 1 for graphite and SiC condensation. Mixing models by Travaglio *et al.* (1999), using the SN compositions by Woosley & Weaver (1995), reproduce the observed ^{12}C/^{13}C, ^{18}O/^{16}O, and ^{30}Si/^{28}Si ratios, and the inferred ^{26}Al/^{27}Al, ^{41}Ca/^{40}Ca, and ^{44}Ti/^{48}Ti ratios if jets of material from the inner Si-rich zone penetrate the intermediate O-rich zones and mix with matter of the outer C-rich zones. However, the models give less ^{15}N and ^{29}Si than seen in the grains (Nittler *et al.* 1995; Travaglio *et al.* 1999; Hoppe *et al.* 2000), and improvements in stellar structure models and reassessments of reaction rates are necessary. For example, the ^{15}N yield significantly increases when stellar rotation is taken into account, and the ^{26}Mg(α,n)^{29}Si reaction, which is highly temperature dependent, is poorly determined for $T = (1 \text{-} 4) \times 10^9$ K (e.g., Travaglio *et al.* 1998).

The Zr, Mo, and Ba isotopes in SiC X grains were analyzed with resonant ionization mass spectrometry (Pellin *et al.* 1999; 2000; 2001). Four out of 6 grains have relative ^{95}Mo and ^{97}Mo excesses up to 1.8× solar. Such enrichments are not expected from either the *s*-process (which would enrich mass 96 and 98) nor the *r*-process (which would give the largest excess in mass 100). The excesses in ^{95}Mo and ^{97}Mo can be explained by a neutron burst - akin to a mini *r*-process – occurring in the He-rich zone of an exploding massive star (Meyer, Clayton & The 2000). Excesses in ^{96}Zr and ^{138}Ba in X grains can also be accounted for by this process.

2.2. *Diamond*

Diamond is the most abundant carbonaceous pre-solar mineral, but its origin(s) remain enigmatic. Diamonds are only measurable as aggregates of many nano-size particles that probably came from several different types of sources, including supernovae, as seen from the Xe isotopes. The anomalous Xe (Xe-HL) in diamonds is enriched in both *L*ight (124 and 126) and *H*eavy (134 and 136) isotopes (Lewis *et al.* 1987). These are *p*- and *r*- process

only isotopes, respectively, believed to come from supernovae. It remains a puzzle why the excesses in the light and the heavy isotopes are always correlated because the *p*- and *r*-process are assumed to occur in different places within supernovae. Other heavy elements, e.g., Te and Pd also point to a supernova origin of diamonds (Richter, Ott & Begemann 1998; Maas *et al.* 2001). The SN origin of some of the pre-solar diamonds seems to be supported by the mid-IR spectra of SN 1987A, which show a broad feature at 3.40 and 3.53 μm (Meikle *et al.* 1989), consistent with the identification of surface hydrogenated diamond (Guillois, Ledoux & Reynaud 1999).

One the other hand, diamond aggregates have ^{12}C/^{13}C of 92 - 93 (e.g., Russell, Arden & Pillinger 1996), close to the solar ratio of 89. The ^{14}N/^{15}N ratio of 417-419 (Lewis *et al.* 1987; Russell, Arden & Pillinger 1996) is similar to 435 measured in Jupiter (Owen *et al.* 2001). This may suggest that only a portion of pre-solar diamonds formed in supernovae and prompted the quest for the diamonds' other stellar sources.

3. Pre-solar grains from novae

A handful of pre-solar SiC and graphite grains have low ^{12}C/^{13}C, low ^{14}N/^{15}N, and high ^{26}Al/^{27}Al ratios (Amari *et al.* 2001), consistent with theoretical predictions for ejecta of both CO and ONe novae (Starrfield, Gehrz & Truran 1997; 1998; José & Hernanz 1998; José *et al.* 2004). All grains have ^{30}Si excesses (^{30}Si/^{28}Si up to 2.1 $\times$ solar). The peak temperatures reached in CO novae are not high enough to significantly modify Si isotopic compositions, hence the Si isotopes of the grains indicate they formed in ONe novae. However, to reproduce the grain data it is necessary to mix pure nova ejecta with a huge amount (99%) of close-to-solar material (Amari *et al.* 2001). The apparent lack of known graphite and SiC grains from CO novae agrees with expectations from condensation calculations for nova ejecta (José *et al.* 2004).

Nittler & Hoppe (2005) argued that grains with low ^{12}C/^{13}C and ^{14}N/^{15}N ratios could also form in supernovae. Isotopic analysis of Ti in the grains could distinguish the two stellar sources because Ti isotopes are not modified in novae. Nittler *et al.* (2006) found a SiC grain with ^{12}C/^{13}C $= 1$, which can only be obtained by hot H burning, pointing clearly toward a nova origin.

4. Conclusions

Pre-solar grains from SNe and novae exist. Laboratory analysis of such grains gives us, with unprecedented precision, detailed information about the nucleosynthesis products and grain formation from these stars.

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