Silicon Carbide Grains of Type X and Supernova Nucleosynthesis

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Silicon carbide grains of type X constitute ~1% of all presolar SiC grains found in primitive meteorites. These grains have ^{15}N and ^{28}Si excesses, mostly light C, high inferred $^{26}Al/^{27}Al$ ratios, and evidence (from ^{44}Ca and ^{49}Ti excesses) for the initial presence of the short-lived radioisotopes ^{44}Ti and ^{49}V. These isotopic signatures clearly indicate an origin in the ejecta of Type II supernovae (SNe) and material from different SN zones had to contribute to the mix from which the grains formed: He/N (^{26}Al), He/C (^{12}C and ^{15}N), and the Si/S zone (^{28}Si, ^{44}Ti, ^{49}V). However, in detail there are many discrepancies between grain data and theoretical predictions from SN models. One major discrepancy concerns the distribution of the Si isotopic ratios. In a Si 3-isotope plot, most grains plot along a line, which points to a primary isotopic composition with $^{29}Si/^{28}Si \approx 1/3 \times$solar and almost no ^{30}Si. However, such a composition is not produced by any of the SN models. Another set of discrepancies involves the correlation between C, N and Al isotopic ratios: $^{12}C/^{13}C$ and $^{15}N/^{14}N$ ratios are high in the He/C and low in the He/N zone, whereas the $^{26}Al/^{27}Al$ ratios show the opposite behavior. As a consequence, mixing between these zones results in negative correlations between these ratios, in contrast to the grain data. Another example is the lack of large ^{54}Fe excesses in X grains. While mixing with material from the Si/S zone, rich in ^{28}Si, is necessary to explain the ^{28}Si excesses in these grains, the ^{54}Fe, also abundant in this zone, must have been separated from the ^{28}Si before grain condensation by a process still not understood.

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1. Introduction

Silicon carbide grains of type X make up ~1% of all presolar SiC grains found in primitive meteorites [1]. These grains have high $^{12}C/^{13}C$ and low $^{14}N/^{15}N$ ratios (Fig. 1). They also have large ^{28}Si excesses (Fig. 2) and high inferred (from large ^{26}Mg excesses) $^{26}Al/^{27}Al$ ratios. These isotopic signatures indicate an origin in Type II SNe. Absolute proof for a SN origin comes from evidence for the initial presence of ^{44}Ti ($T_{1/2} = 60$ yrs) in the form of ^{44}Ca excesses. ^{44}Ti is only produced in SNe [2].

Although the isotopic compositions of the grains leave no doubt that they came from SNe, in detail there are many discrepancies between isotopic data and theoretical predictions from SN models [3].
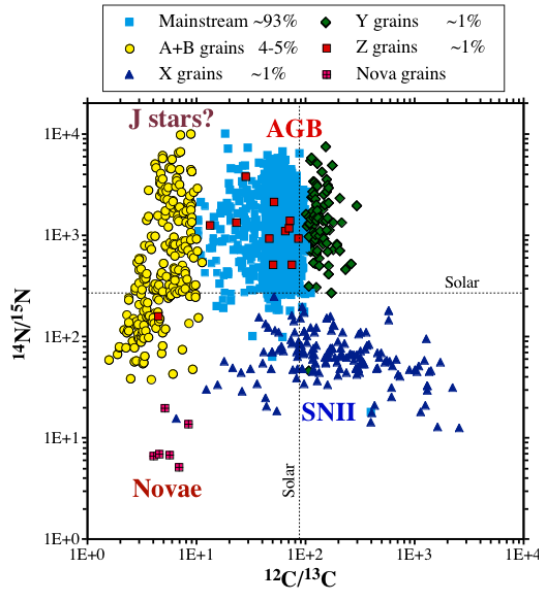

Figure 1. Nitrogen and carbon isotopic ratios of individual presolar SiC grains. The grains can be grouped based on their C, N, Al, and Si isotopic ratios. The isotopic ratios of X grains indicate a SN origin. All isotopic ratios of SiC grains shown in this and subsequent plots are taken from the presolar data base [4].
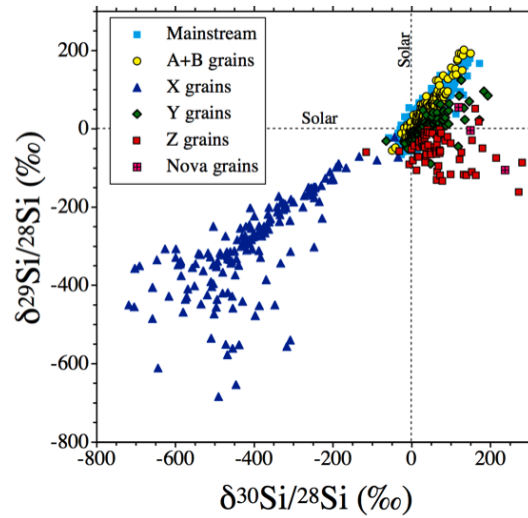
Figure 2. Silicon isotopic ratios of individual presolar SiC grains. The ratios are expressed in δ–values, deviations from the solar ratios in parts per thousand (‰). X grains show ^{28}Si excesses.

2. Isotopic ratios and comparison with SN models

We compare selected isotopic ratios in X grains with SN predictions. Fig. 3 shows isotopic ratios (normalized to solar ratios) and isotopic abundances in the interior layers of the 25 M$_{\odot}$ SN model s25a28d (http://nucastro.org/nucleosynthesis/) by Rauscher et al. [5]. The He/N and He/C zones are the only regions with C>O. ^{28}Si, ^{44}Ti, and ^{49}V are produced in the inner Si/S and O/Si zones. The isotopic ratios of X grains and the condition of C>O for SiC condensation require mixing of material from different SN layers.
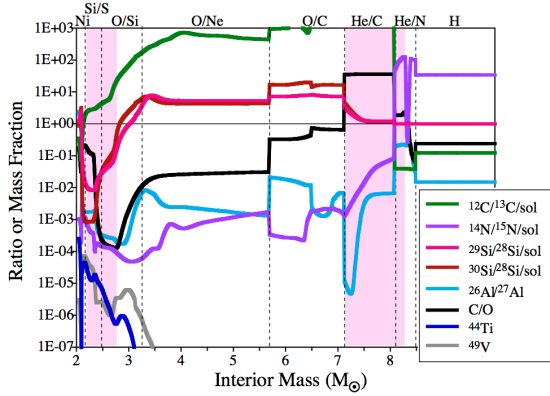
Figure 3. Theoretical predictions of the isotopic abundances and ratios in the interior of a 25 $M_\odot$ supernova from the model by Rauscher et al. [5]. For stable isotopes the isotopic ratios are normalized to the solar ratios; for the short-lived radioisotopes ^{44}Ti and ^{49}V the mass fractions are given. Also given is the C/O ratio. C/O>1 is believed to be a necessary condition for the condensation of SiC. The isotopic signatures of X grains indicate mixing between the zones with pink color.

2.1. Carbon, nitrogen and aluminum isotopic ratios

Mixing between the He/N and He/C zone (Fig. 4) can reproduce the C and N isotopic ratios of most X grains but only if one takes material from the layer with the ^{15}N spike (sharp crevice in the ^{14}N/^{15}N ratio at 8.33 $M_\odot$) in the He/N zone (Fig. 3). Even then, there are grains that plot below the lowest mixing line. In addition, not all SN models (other masses or [6]) have the ^{15}N spike. This is an issue that needs exploration.

The situation is worse for the Al isotopic ratios. Mixing between the He/N (high ^{26}Al/^{27}Al and low ^{12}C/^{13}C) and He/C zone (low ^{26}Al/^{27}Al and high ^{12}C/^{13}C; Fig. 5) produces an anticorrelation between the ^{26}Al/^{27}Al and ^{12}C/^{13}C ratios (same mixing curves as in Fig. 4). However, the grain data do not show this (Fig. 5). In addition, some grains have higher ^{26}Al/^{27}Al ratios than those produced in any of the layers of the SN models.
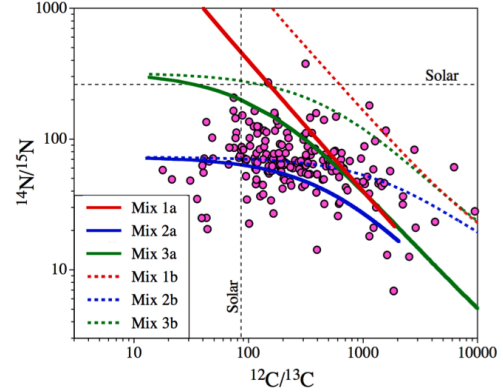

Figure 4. Nitrogen isotopic ratios of X grains plotted against the C isotopic ratios. The lines are predicted isotopic ratios obtained by mixing layers from the He/C zone (**a**: at 7.24 $M_\odot$, **b**: at 7.6 $M_\odot$ interior mass) with layers of the He/N zone (**1**: at 8.2 $M_\odot$, **2**: at 8.33 $M_\odot$ (^{15}N spike), **3**: 20% of the He/N zone centered at the ^{15}N spike at 8.33 $M_\odot$) of the 25 $M_\odot$ supernova model by Rauscher et al. [5].
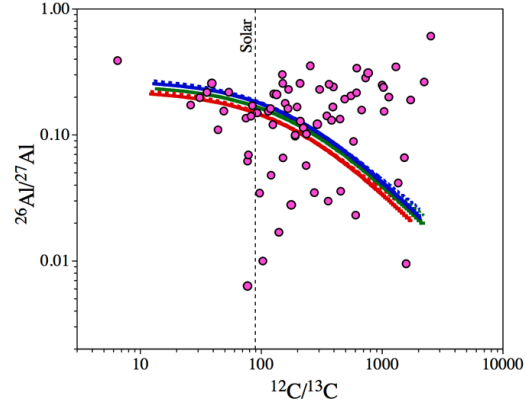

Figure 5. Inferred Al isotopic ratios of X grains plotted against the C isotopic ratios. The lines are predicted isotopic ratios obtained by mixing layers as in Fig. 4.

2.2. Silicon isotopic ratios

Mixing between at least three different zones (e.g., Si/S, O/Ne and He/C) is required to explain the Si isotopic compositions of X grains (Fig. 6). However, this requires completely ad hoc assumptions and does not explain the trend shown by most X grains. A primary component close to the star symbol is required to account for this trend.
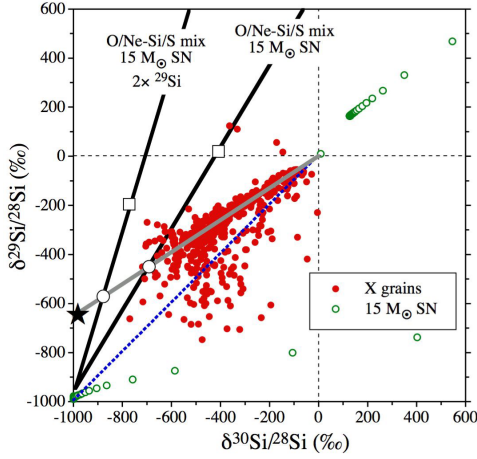
Figure 6. Silicon isotopic ratios of X grains are compared to ratios predicted by the 15 $M_\odot$ supernova model by Rauscher et al. [5]. The gray line is the correlation line for most X grains. The broken blue line represents a mix between the Si/S zone and the He/N and He/C zones. Points on the gray correlation line can be reached by mixing contributions from the O/Ne zone with the Si/S zone. The black star represents a putative primary composition that would best explain the gray correlation line.

2.3. Titanium and iron isotopic ratios

In the Si/S zone there are high abundances of ^{46}Ti and ^{54}Fe (Fig. 7). Since ^{28}Si from this zone is needed to explain the ^{28}Si excesses in X grains (Fig. 3), one expects to find large ^{46}Ti and ^{54}Fe excesses. However, the grain data do not show such excessses [3,
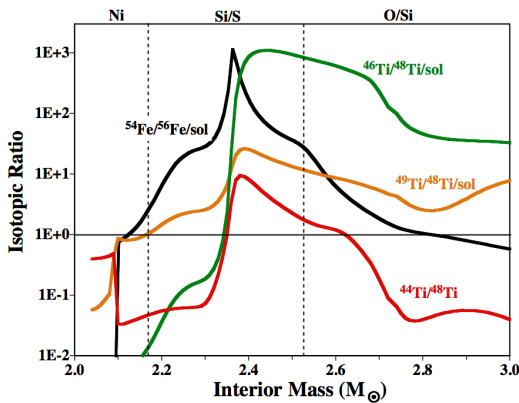

Figure 7. Titanium and Fe isotopic ratios in the inner SN zones predicted from the 25 $M_\odot$ supernova model by Rauscher et al. [5]. Ratios of stable isotopes (for ^{49}Ti after decay of ^{49}V) are normalized to solar ratios.

7]. The lines in Fig. 8 show compositions expected for mixtures of He/N-He/C material, which has a δ^{46}Ti/^{48}Ti value close to 0 ‰, with material from different layers in the Si/S and O/Si zones. If only material from the inner Si/S zone contributes, then large ^{46}Ti excesses can be avoided. However, even then large ^{54}Fe excesses are expected, which are not observed (Fig. 9).
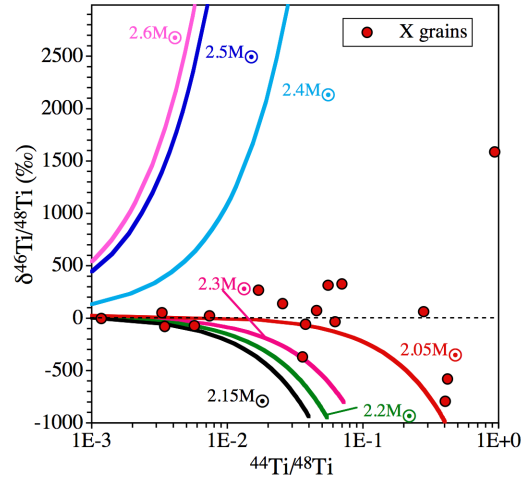

Figure 8. Titanium isotopic ratios of X grains and compositions expected for mixtures of He/N-He/C material with material from different layers (interior mass labels in the plot) in the Si/S and O/Si zones of the 25 $M_\odot$ supernova model by Rauscher et al. [5].
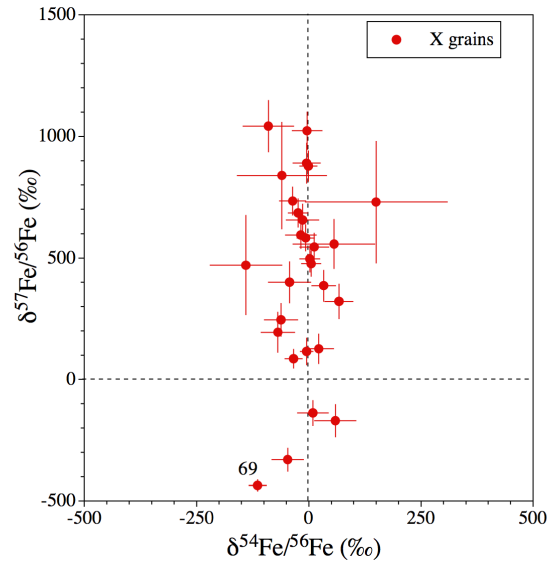

Figure 9. Iron isotopic ratios of X grains [7].

3. Conclusions

We have shown that in several cases SN models do not produce isotopic ratios measured in SN grains in great detail, especially correlations between isotopic systems. At present, it is not clear where improvements could be found. We have to explore a larger range of stellar masses and look at models including stellar rotations. However, it is clear that one-dimensional models of SN nucleosynthesis are far too simplistic. Mixing is one of the poorly understood processes that play an important role in SN nucleosynthesis. Two- and three-dimensional models show that mixing between different SN zones is extremely complex, with material from inner layers ploughing into or overtaking outer layers [8, 9]. Following multi-dimensional mixing with nuclear reaction networks exceeds present computer capabilities and we have to await progress. Another question is how the condensation behaviour of various species affects what elements of a given zone end up in a SN grain [10]. For example, Fe from the Si/S zone might condense into FeS grains and could be separated from the Si, so that Fe from this zone was not included in the X grains, whereas Si was. Presently, this is pure conjecture. However, it might be possible to perform condensation calculations while following multi-dimensional mixing [11] and obtain information about possible fractionation between different elements. Thus, while we are still far away from an understanding of the discrepancies between grain data and SN model, we can see several paths to be taken that might lead to progress.

Acknowledgments

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