PRODUCTION OF CARBON-RICH PRESOLAR GRAINS FROM MASSIVE STARS

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ABSTRACT

About a year after core-collapse supernova, dust starts to condense in the ejecta. In meteorites, a fraction of C-rich presolar grains (e.g., silicon carbide (SiC) grains of Type-X and low density graphites) are identified as relics of these events, according to the anomalous isotopic abundances. Several features of these abundances remain unexplained and challenge the understanding of core-collapse supernovae explosions and nucleosynthesis. We show, for the first time, that most of the measured C-rich grain abundances can be accounted for in the C-rich material from explosive He burning in core-collapse supernovae with high shock velocities and consequent high temperatures. The inefficiency of the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction relative to the rest of the $\alpha$-capture chain at $T > 3.5 \times 10^8$ K causes the deepest He-shell material to be carbon-rich and silicon-rich, and depleted in oxygen. The isotopic ratio predictions in part of this material, defined here as the C/Si zone, are in agreement with the grain data. The high-temperature explosive conditions that our models reach at the bottom of the He shell can also be representative of the nucleosynthesis in hypernovae or in the high-temperature tail of a distribution of conditions in asymmetric supernovae. Finally, our predictions are consistent with the observation of large $^{44}\text{Ca}/^{40}\text{Ca}$ observed in the grains. This is due to the production of $^{44}\text{Ti}$ together with $^{40}\text{Ca}$ in the C/Si zone and/or to the strong depletion of $^{40}\text{Ca}$ by neutron captures.

Key words: stars: abundances – stars: evolution – stars: interiors

Online-only material: color figures

1. INTRODUCTION

Massive stars ($M > 8\,M_\odot$) are among the major contributors to the chemical enrichment of the galaxy through both their winds and core-collapse supernova (CCSN). In carbonaceous meteorites several types of C-rich presolar grains condensed in CCSN ejecta have been identified through association of the measured isotopic abundance patterns with signatures of such events (see, e.g., Zinner 2003; Clayton & Nittler 2004). Among those, C-rich grains like Type X silicon carbides (SiC-X) and graphites are assumed to require a C-rich environment to form (C/O > 1, e.g., Travaglio et al. 1999).

Standard massive star models predict that C-rich ejecta originate in explosive He shell burning, characterized by partial pre-explosive He-burning products (e.g., Woosley & Weaver 1995). The heavy species abundances show a mild s-process signature from pre-explosive convective He-shell burning (triggered by the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction; e.g., Rauscher et al. 2002), and by the explosive neutron burst triggered again by the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction (namely the n-process, with $n_n \sim 10^{18} \text{cm}^{-3}$; e.g., Blake & Schramm 1976; Meyer et al. 2000).

SiC-X grains show a $^{28}\text{Si}$ excess compared to $^{29,30}\text{Si}$, and most of these grains have a $^{12}\text{C}$ and $^{15}\text{N}$ excess while some show a $^{13}\text{C}$ and $^{15}\text{N}$ excess. The $^{26}\text{Mg}$ and $^{44}\text{Ca}$ excess compared to solar has been explained by the condensation of unstable $^{26}\text{Al}$ and $^{44}\text{Ti}$ into the grains (e.g., Amari et al. 1992; Nittler & Alexander 2002; Besmehn & Hoppe 2003). Graphite grains (with low density, LD group; Amari et al. 1995) show a large range of $^{13}\text{C}/^{12}\text{C}$ ratio, possibly correlated with $^{18}\text{O}$ excess. Both an excess and deficit of $^{30}\text{Si}$ with respect to $^{28,29}\text{Si}$ can be observed. Indication of $^{26}\text{Mg}$ and $^{44}\text{Ca}$ excess is also found for several of those grains. Finally, their measured $^{34}\text{N}/^{15}\text{N}$ ratio with few exceptions is quite normal, pointing to a contamination from solar nitrogen (e.g., Zinner 2003 and references therein).

To explain these abundance signatures, Travaglio et al. (1999) and Yoshida (2006) assume mixing of He-shell matter with Si/S zone material (see Meyer et al. 1995) deeper in the supernova without any mixing contribution from the O-rich layers in between. The main constraint is that the material out of which the grains form needs to be C-rich to have free carbon to condense in SiC and graphites after CO formation. Clayton (2013) and references therein suggests instead that since SN ejecta are not in thermodynamic equilibrium, C-rich grains may condense in O-rich and $^{28}\text{Si}$-rich ejecta.

More recently, Marhas et al. (2008) found a deficit or normal $^{54}\text{Fe}$ compared to $^{56}\text{Fe}$ abundance in SiC-X grains, in disagreement with nucleosynthesis predictions for the $^{28}\text{Si}$-rich Si/S zone to be $^{56}\text{Fe}$-rich (e.g., Thielemann et al. 1996). Possible fractionation between Si and Fe proposed by Marhas et al. (2008) is unlikely to be sufficient, since Fe-rich subgrains in the SiC-X grains also show a normal $^{54}\text{Fe}/^{56}\text{Fe}$ ratio.
In this Letter we propose a new nucleosynthesis scenario, where the observational signatures of C-rich presolar grains can be obtained without mixing from the C-rich material in CCSN that experience a strong shock. The Letter is organized as follows. In Section 2 we describe stellar models and the nucleosynthesis calculations, in Section 3 we compare theoretical results with measurements for SiC X grains and graphite grains. Finally, in Section 4 results are summarized.

2. STELLAR MODEL CALCULATIONS AND NUCLEOSYNTHESIS

In this study, we consider three SN explosion models for a 15 $M_\odot$, $Z = 0.02$ star. (M. Pignatari et al. 2013, in preparation). The pre-supernova evolution is computed with the stellar code GENEC (for more details see Bennett et al. 2012, model 15ST in their Figure 6). The explosion simulations include the fallback prescription by Fryer et al. (2012), using the recommended initial shock velocity and reduced by a factor of two and four, respectively (models 15r, 15r2 and 15r4). The standard initial shock velocity used beyond fallback is $2 \times 10^9$ cm s$^{-1}$. For a 15 $M_\odot$ star simulation by Fryer et al. (2012), a $2 \times 10^9$ cm s$^{-1}$ shock velocity corresponds to a $3-5 \times 10^{51}$ erg explosion, a $1 \times 10^9$ cm s$^{-1}$ shock velocity corresponds to a $1-2 \times 10^{51}$ erg explosion, and the $5 \times 10^8$ cm s$^{-1}$ shock velocity corresponds to a weak explosion below $10^{51}$ erg.

The full nucleosynthesis is calculated using the post-processing code MPPNP (see, e.g., Bennett et al. 2012). Here we focus only on C-rich explosive He burning ejecta which include the He/C zone and a small part of the O/C zone (Meyer et al. 1995).

Compared to standard symmetric CCSN models with explosion energy of $10^{51}$ erg (e.g., Woosley & Weaver 1995), our models show that depending on the explosion energy $^{16}$O is depleted and $^{28}$Si is accumulated at the bottom of the He/C zone and at the top of the C/O zone, where $^{12}$C is not significantly modified (see Figure 2 for the details of models 15r and 15r4 with the largest and smallest shock). Such $^{28}$Si-enrichment is also obtained in the intermediate model 15r2. Similar nucleosynthesis signatures and high temperature conditions are also predicted in high energy ejecta of aspherical SN and in hypernovae (e.g., Nomoto et al. 2009).

At temperatures above $\sim 3.5 \times 10^8$ K the $(\alpha, \gamma)$-rates of $^{16}$O and $^{20}$Ne exceed the $^{12}$C$(\alpha, \gamma)$-rate (Figure 1). The reaction rate is directly correlated with the S-factor. The rate is obtained by integrating the S-factor over the Gamow window, the energy range of stellar burning at a certain temperature as defined by Caughlan et al. (1985). The S-factor curve of $^{12}$C$(\alpha, \gamma)^{16}$O is characterized by non-resonant reaction components: they primarily consist of interfering E1 transitions from tails of broad high energy $^1$S resonances and the $^1$S sub-threshold state, and a E2 direct capture component interfering with low energy tails of $^2$S resonances and the subthreshold state (Buchmann & Barnes 2006). While at low temperatures the reaction rate is lower than $^{16}$O$(\alpha, \gamma)^{20}$Ne, it declines toward higher temperatures because of the decline of the S-factor by two orders of magnitude. The $^{16}$O$(\alpha, \gamma)^{20}$Ne reaction rate, on the other hand, is determined by a constant non-resonant S-factor term and by the narrow $^3$ and $^1$S resonances at 1.1 MeV and 1.3 MeV, respectively, which dominate the reaction rate above temperatures of $T \sim 10^8$ K (Costantini et al. 2010). Concerning the reaction rates of the subsequent $\alpha$-capture reactions $^{20}$Ne$(\alpha, \gamma)^{24}$Mg (Schmalbrock et al. 1983) and $^{24}$Mg$(\alpha, \gamma)^{28}$Si (Strandberg et al. 2008), the non-resonant S-factor terms are larger and the critical energy range above 0.3 MeV is characterized by narrow resonances which cause a further enhancement in the reaction rate, as demonstrated for $^{28}$Si$(\alpha, \gamma)^{32}$Mg in Figure 1. This is also true but for larger energies and to a smaller extent for the production of $^{32}$S, $^{36}$Ar, $^{40}$Ca, and $^{44}$Ti.

In parts of the He/C and C/O zones, $^{16}$O is thus depleted and feeds the production of $^{28}$Si. This zone is C- and Si-rich, and therefore we call this zone the C/Si zone. A fundamental condition required to form the C/Si zone is that sufficient $^4$He fuel is available while high enough temperatures are reached in the explosive burning.

For model 15r, $^{16}$O and $^{20}$Ne are depleted, whereas $^{28}$Si and $^{32}$S are produced up to a mass fraction of $\sim 20\%$ in the C/Si zone due to reactions along the $\alpha$-capture chain (Figure 1). As shown in Figure 2, the $\alpha$-capture chain is efficient up to $^{44}$Ti. At the bottom of the He/C zone results are similar, but since the pre-explosive $^{16}$O abundance is lower the production of $^{28}$Si and $^{32}$S is less efficient. In this zone $^{40}$Ca is depleted via neutron captures, and unstable $^{44}$Ti is not produced. In model 15r4 the most produced species in the C/Si zone are $^{28}$Ne, $^{24}$Mg and $^{28}$Si. In comparison with the pre-explosive abundances, the species above $^{32}$S and along the $\alpha$-chain are not produced efficiently. A similar but milder signature is obtained again at the bottom of the He/C zone. Note that the rapid decrease of $\alpha$-particles in the...
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Figure 2. Abundances profiles in the C-rich material for H, $^4$He, $^{12}$C, $^{16}$O and $^{28}$Si before (thin lines) and after (thick lines) the supernova explosion for models 15r and 15r4 (upper left and right panels, respectively). The same is shown in more detail and for more species in the lower panels. The C/Si zone is where O is depleted producing $^{28}$Si, above $2.945 M_\odot$. The process of O-depletion affects a large part of the He/C zone, up to $M = 3.3 M_\odot$ and $3.2 M_\odot$ for models 15r and 15r4, respectively.

(A color version of this figure is available in the online journal.)

O/C zones causes a weaker O-depletion (and $^{28}$Si excess). Before the SN explosion such a zone is radiative, and still carries the signature of the pre-explosive convective He-burning core. The He profile under the He shell depends on uncertain physics assumptions in the models. Furthermore, $^4$He may be mixed into the O/C zone from the bottom of the He shell by extra-mixing triggered by processes that have not been considered in our pre-SN model, such as rotation (e.g., Meynet et al. 2006) or convective boundary mixing (e.g., Meakin & Arnett 2007). In that case larger fractions of the O/C zone would be converted into the C/Si zone compared to our model.

In summary, in the CCSN ejecta exposed to strong shocks the upper part of the C/O zone and an extended region of the He/C zone are $^{16}$O-depleted and $^{28}$Si-rich, and $^{28}$Si will be present in C-rich material when grains will start to condense.

3. COMPARISON WITH OBSERVATIONS

In this section, the nucleosynthesis predictions described in Section 2 are compared with observations for single SiC-X and graphite grains from the St. Louis Presolar Grains Database (Hynes & Gyngard 2009). We compare only the abundances from the C-rich region in the He shell (namely, the C/Si zone and the He/C zone). Mildly C-rich regions in the He/N zone (H-burning layer) will be discussed in a future work.

In Figure 3, left panel, C and N isotopic ratios for SiC-X grains are shown compared to the abundances in C-rich material from our models. Not included in the figure, LD graphites show a similar $^{12}$C/$^{13}$C spread compared to SiC-X grains. The C/Si zone and the bottom of the He/C zone show high $^{12}$C/$^{13}$C and low $^{14}$N/$^{15}$N. The carbon isotopic ratio is at least 3 orders of magnitude larger than that of the grains due to lack of $^{13}$C (area labeled as “Si-rich” in the plot). Grains data are located in between our predictions and the solar ratios. Some mixture with a normal component and/or with material from the external part of the He shell is required to fit the observations in this scenario. Indeed, in the most external part of the He/C zone (the part that is not O-depleted) the C ratio evolves to normal values, but with a N ratio larger than solar. Note that in Figure 3 there is a group of SiC-X grains showing $^{12}$C/$^{13}$C lower than solar. We will discuss them in a future work, where SN ejecta affected by H burning are considered. In Figure 3, we report the comparison with LD graphites for $^{16}$O/$^{18}$O, and again $^{12}$C/$^{13}$C. The largest measured $^{18}$O excess is observed for few graphites.
The C\textsuperscript{28}Si excess is reproduced in part of the C/Si ratio, and with 12C/\textsuperscript{13}C larger than solar, in agreement with the abundance signature in the external part of the He/C zone. In the C/Si zone and at the bottom of the He/C zone the \textsuperscript{16}O/\textsuperscript{18}O becomes up to 7–8 orders of magnitude larger than solar. However, such a large ratio can be reduced to a ratio ~ solar with minor mixing with normal material, since there is negligible amount of oxygen left in these layers (see, e.g., Figure 2).

In Figure 4, right panels, the Si isotopic ratio of stellar models and SiC-X grains are compared. The same is done for LD graphites in the bottom left panel. In the upper left panel, the pre-explosive and post-explosive isotopic Si abundances are reported for model 15r. During the explosion, in the C/O zone with low \textit{α}-fuel available, \textsuperscript{28}Si is marginally produced via \textit{α}-capture, and \textsuperscript{29,30}Si are strongly produced via neutron capture. The C/Si zone shows a strong \textsuperscript{28}Si production. In particular, in zone 1 (M = 2.95 M\textsubscript{⊙}) the pre-explosive temperature and density are 3.1 × 10\textsuperscript{9} K and 1.34 × 10\textsuperscript{3} cm\textsuperscript{-3}, rising up to 2.0 × 10\textsuperscript{9} K and 7.58 × 10\textsuperscript{3} cm\textsuperscript{-3}, respectively, during the explosion. Moving outward in the deepest part of the He/C zone, the \textit{n}-process (e.g., Meyer et al. 2000) gradually changes the \textsuperscript{28}Si-enrichment to strong \textsuperscript{29,30}Si-enrichments. Less extreme Si isotopic ratios with a mild \textsuperscript{29,30}Si excess are seen in the external He/C zone due to the pre-explosive \textit{s}-processing. The \textsuperscript{28}Si excess is reproduced in part of the C/Si zone for models 15r and 15r2 (see, e.g., zone 1 in model 15r, Figure 4, upper left panel and right bottom panel). Also in this case, the grains data shows δ-values closer to the solar ratio, corresponding again to some mixing with unprocessed material, or with more external C-rich stellar layers. On the other hand, in model 15r4 the shock temperature is not sufficient to reproduce the \textsuperscript{28}Si excess observed in SiC-X grains. The combined nucleosynthesis contribution from \textit{α}-captures and neutron captures cause a milder \textsuperscript{28}Si/\textsuperscript{29}Si-enrichment compared to \textsuperscript{28}Si/\textsuperscript{29}Si moving outward in the \textsuperscript{28}Si-rich regions, and an earlier positive δ(\textsuperscript{30}Si) with decreasing temperature compared to δ(\textsuperscript{28}Si). This trend is consistent with a subset of SiC-X grains, whereas most of the SiC-X grains belong to the group X1 (Lin et al. 2002).

Finally, in Figure 4, left bottom panel, LD graphites show a relevant amount of grains with \textsuperscript{28}Si excess, but with many scattered around the solar ratios, and few with positive Si δ ratios. This different behavior between SiC-X grains and graphites is qualitatively explained looking at the profile of Si isotopes in model 15r (Figure 4, left upper panel). The efficiency of graphite condensation depends on the C enrichment only, whereas SiC-X grains depend on both the C and Si inventory. Therefore, SiC-X condensation will be more efficient in the C/Si zone than in the He/C zone, whereas constraints for graphites are less severe. We may also expect that the condensation of SiC-X and graphites will be less efficient in the external part of the He/C zone, compared to the C-rich and O-depleted regions. Indeed, in these stellar layers there is less free C and Si available. Simulations of the condensation processes using present abundance predictions are required to better quantify this analysis.

The initial \textsuperscript{44}Ti and \textsuperscript{26}Al enrichment are distinctive signatures for a significant fraction of SiC-X grains and LD graphites (e.g., Clayton & Nittler 2004). Their initial amount that condenses into the grains is usually estimated assuming that the \textsuperscript{44}Ca/\textsuperscript{40}Ca and \textsuperscript{26}Mg/\textsuperscript{24}Mg ratios are solar. This is not the case in our calculations (see, e.g., \textsuperscript{40}Ca abundance profile in Figure 2). Furthermore, Al and Ti condense more efficiently than Mg and Ca, respectively (e.g., Amari et al. 1995; Besmehn & Hoppe 2003). For model 15r, the thermodynamic conditions allow to produce \textsuperscript{40}Ca and \textsuperscript{44}Ti at the same time, with \textsuperscript{44}Ti/\textsuperscript{40}Ca = 10\textsuperscript{−2} (Figure 2). The largest measured \textsuperscript{44}Ca/\textsuperscript{40}Ca ratio in SiC-X grains of ~2–3 (Hynes & Gyngard 2009) would be satisfied with a fractionation Ti/Ca ~ 100 without considering also direct \textsuperscript{44}Ca production. In the He/C zone, the neutron captures deplete the pre-explosive \textsuperscript{40}Ca by orders of magnitude, eventually leading to high \textsuperscript{44}Ca/\textsuperscript{40}Ca and high \textsuperscript{48}Ca/\textsuperscript{40}Ca. \textsuperscript{48}Ti is depleted in this case. We note that in measurements by, e.g., Besmehn & Hoppe (2003) \textsuperscript{48}Ca and \textsuperscript{48}Ti were not possible to distinguish. For model 15r, the abundances in the C/Si zone are less extreme than model 15r, with a nucleosynthesis more similar to the He/C zone.

One of the main puzzles for the previous ad-hoc mixing scenarios for SiC-X grains is the non-enhancement of \textsuperscript{54}Fe compared to \textsuperscript{56}Fe, since in standard CCSN models \textsuperscript{28}Si-rich zones are also \textsuperscript{54}Fe-rich. In the C/Si zone of our models Fe species are destroyed by neutron captures and grain signatures.
with low $^{54}$Fe are predicted. The isotopes $^{57,58}$Fe can also be produced outward in the He/C zone.

4. CONCLUSIONS AND FINAL REMARKS

We have compared the abundance signature in presolar SiC-X grains and LD graphites with nucleosynthesis predictions from CCSN ejecta exposed to high shock velocities. Due to basic nuclear properties, an $\alpha$-capture chain starts from $^{16}$O feeding heavier species including $^{28}$Si, without affecting the pre-explosive abundance of $^{12}$C and creating a new C/Si zone. The amount and distribution of $\alpha$-isotopes mainly depend on the abundance of the seed $^{16}$O, on the explosion shock velocity and on the amount of $\alpha$-particles available. The interplay between the $\alpha$-captures and the $n$-process regulates the relative abundances of $^{28,29,30}$Si in the He/C zone.

The typical isotopic trends for C, N, and O of LD graphites and SiC-X grains can be reproduced using the C-rich ejecta, with the exception of grains with low $^{12}$C/$^{13}$C. The observed $^{28}$Si excess is explained qualitatively from the signature in the C/Si zone, where $^{16}$O has been depleted by following $\alpha$-captures to build $^{28}$Si and other heavier species. Since production of graphites depends only on the C abundance, and SiC-X on both C and Si, this may explain why the $^{28}$Si excess is not observed in all LD graphites. Therefore, the C/Si zone is an ideal environment to condense SiC-X and LD graphites. Such abundance signatures triggered by high temperatures can be also obtained in parts of asymmetric CCSN ejecta exposed to high shock velocities, or in hypernovae ejecta.

We reconsidered the $^{44}$Ti excess extrapolated from a sample of C-rich presolar grains. In the C/Si zone the $^{44}$Ca/$^{40}$Ca is not solar, affecting the results of such extrapolation. The Ca and Ti condensation efficiency is uncertain, leading to their elemental fractionation. For the model with the largest explosion energy (model 15r) both $^{40}$Ca and $^{44}$Ti (and $^{48}$Ti) are produced in the C/Si zone (with $^{40}$Ca/$^{44}$Ti $\sim$ 100). Neutron captures destroy $^{40}$Ca in the He/C zone. The isotope $^{44}$Ca (and $^{48}$Ca) instead is produced by neutron captures in all the O-depleted and C-rich ejecta. For weaker shocks (see, e.g., model 15r4) neutron captures dominate the Ca nucleosynthesis, $^{40}$Ca is depleted and $^{44}$Ca produced. In both cases, a comparison needs to be made grain-by-grain, where correlations with, e.g., Ti species and $^{28}$Si excess (e.g., Clayton & Nittler 2004) are considered. A similar discussion can be derived for $^{26}$Al enrichment.

Finally, the present results provide support for the existence of different energy components in the ejecta of the same CCSN. Asymmetries during the SN explosion of, e.g., SN1987A and CasA are confirmed by observations. In SN1987A the emission Si i and Fe i–ii from core material are correlated with He i emission, possibly indicating the signature of $\alpha$-rich freezeout.

**Figure 4.** Si abundances in the Si-rich material for model 15r before and after CCSN (upper left panel). Si isotopic ratios in δ notation ($\delta$ = (stellar ratio/solar ratio − 1) × 1000) is given for SiC-X grains (upper right panel and zoomed in the lower right panel) and LD graphites (lower left panel) compared with models. The Si abundances in model 15r and the correspondent δ-values are highlighted for four zones, at $M = 2.95, 3.15$ (zones 1 and 2), 3.3 and 4 $M_\odot$ (zones 3 and 4, out of the x-axis range in the upper left panel). (A color version of this figure is available in the online journal.)
during high-energy-SN explosion in at least part of the ejecta (Kjær et al. 2010). In CasA, DeLaney et al. (2010) reported two major velocity components for Si II in the ejecta. We suggest that they may be the signature of the Si/S-Si/O and C/Si zones, respectively. This scenario would also explain the non-correlation between Ne II and O IV emission in CasA (Isensee et al. 2010). Indeed, Ne (together with Mg, S, Ar and Ca) could be produced also in the C/Si zone, whereas for standard CCSN O and Ne are produced in the same regions.

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