A NEW METHOD FOR CONSTRAINING EXPLOSIVE ENVIRONMENTS IN TYPE II SUPERNOVAE USING PRE-SOLAR SILICON CARBIDE X GRAIN ISOTOPIC DATA. N. Liu\textsuperscript{1}, B. S. Meyer\textsuperscript{2}, L. R. Nittler\textsuperscript{3} and C. M. O’D. Alexander\textsuperscript{3}, \textsuperscript{1}Department of Physics, Washington University in St. Louis, St. Louis, MO 63130, USA, nliu@physics.wustl.edu, \textsuperscript{2}Department of Physics and Astronomy, Clemson University, Clemson, SC 29634, USA. \textsuperscript{3}Department of Terrestrial Magnetism, Carnegie Institution for Science, Washington, DC 20015, USA.

**Introduction:** X grains constitute 1–2% of all presolar SiC found in primitive extraterrestrial materials \cite{1}. The high initial abundances of a number of short-lived nuclides (e.g., \textsuperscript{26}Al, \textsuperscript{44}Ti and \textsuperscript{49}V) in X grains, point to an origin in Type II supernovae (SNII). Moreover, multi-element isotopic data strongly suggest that X grains sourced materials across different SNII zones \cite{2}. On the other hand, type C grains and a few ungrouped grains (<0.1% in population) are probably also sourced from SNII \cite{3,4}. Given that mixing among different SNII zones during the explosion is extremely complex and poorly understood, it is quite a challenge to provide quantitative constraints on SNII model calculations, because one has too many degrees of freedom (e.g., relative mixing ratios) when attempting to reproduce the isotopic composition of an X grain using SNII nucleosynthesis model predictions. To make the problem worse, there exist large uncertainties in SNII model predictions. Recent SNII models from \cite{5} predict the occurrence of explosive H burning during the explosion. Bona fide SNII grains hold great potential to test this possibility. It is, however, quite challenging to solely investigate the effect of this process by data-model comparison while excluding uncertainties resulting from the mixing process. Here we propose a new method of constraining explosive SNII environments by excluding contribution from the mixing process, based on which we will examine different SNII models.

**Methods:** Compared to the ad hoc mixing approach adopted in previous studies, we will instead use \(\delta^{29,30}\)Si values of SNII grains as a proxy for the degree of mixing between inner and outer SNII zones. Previous studies have shown the following facts. (1) The wide range of negative \(\delta^{29,30}\)Si values of X grains results from mixing of almost pure \(28\)Si-rich material from the inner Si/S zone with more \(29,30\)Si-rich material from the outer region (He/C zone, He/N zone, and H envelope). Thus, more negative \(\delta^{29,30}\)Si values correspond more material from the Si/S zone \cite{1,2}. (2) X grains show \textsuperscript{44}Ti and \textsuperscript{49}V excesses that are correlated with their \(\delta^{29,30}\)Si values, corresponding to positive correlations of \textsuperscript{44}Ti and \textsuperscript{49}V with \textsuperscript{28}Si. The correlations can be used to provide constraints on the production ratios of \textsuperscript{44}Ti/\textsuperscript{48}Ti in the Si/S zone \cite{6} and \textsuperscript{49}Ti/\textsuperscript{50}Ti in the He/C zone \cite{4}. (3) The positive \(\delta^{29,30}\)Si values of type C and ungrouped SNII SiC grains are consistent with them incorporating less material from the Si/S zone compared to X grains \cite{3,4}. As a result, the isotopic compositions of C and ungrouped SNII grains are more representative of nucleosynthesis signatures in the outer SNII region.

To compare with X grain data, we conducted new nucleosynthesis calculations based on the simplified SNII model presented in \cite{7}. For the present study, we computed the explosive nucleosynthesis for an initially 25 \(M_\odot\) presupernova model from \cite{8} with explosion energies of \((1–10)\times10^{51}\) ergs. In this abstract, by comparing the constrained \(\textsuperscript{26}Si/\textsuperscript{30}Si, \textsuperscript{44}Ti/\textsuperscript{48}Ti, \) and \(\textsuperscript{49}Ti/\textsuperscript{50}Ti\) ratios with this new set of SNII model predictions, we will provide new insights into the production of Si isotopes and \textsuperscript{26}Al in SNII and discuss the implications for explosive SNII environments.

**Fig. 1.** Silicon 3-isotope plot comparing X grains \cite{9} with SNII models. The numbers are the explosion energies \((\times10^{51}\) ergs) of the corresponding models.

\(\textsuperscript{29}Si/\textsuperscript{30}Si, \textsuperscript{26}Al\) and \textsuperscript{44}Ti: Figure 1 illustrates that the predicted Si isotope ratios in the Si/S zone depend strongly on the explosion energy. The majority of X grains lie along a line with a slope of ~2/3; Fig. 1 implies that this could be explained if their parent SNII had quite high explosion energies \((>7\times10^{51}\) ergs) in the center. Figure 2 further illustrates that in such high energy explosions, the Si/S zone produces abundant \textsuperscript{26}Al with the predicted \(\textsuperscript{26}Al/\textsuperscript{27}Al\) ratios reaching above unity, which can therefore account for the high inferred initial \(\textsuperscript{26}Al/\textsuperscript{27}Al\) ratios \((>0.1\) in general) observed in X grains \cite{e.g. 2,4,6}. The high energetic explosive environment in the Si/S zone also explains the fact that X grains show the highest initial \(\textsuperscript{26}Al/\textsuperscript{27}Al\) ratios among different presolar SiC groups, while types C and ungrouped SNII grains that sampled more material from the outer region generally had much lower ratios \cite{9}. The inferred explosion energies \((>7\times10^{51}\) ergs), however, are much higher than those \((0.5–3\times10^{51}\) ergs)
inferred for a few SNII (10–25 M\(_{\odot}\)) based on astronomical observations [10].

\[ \text{Isotope Ratio} \]

\[ \text{Explosion Energy (x10^{51} \text{ ergs})} \]

\[ \begin{array}{|c|c|c|}
\hline
\text{Models for 25 M\(_{\odot}\) SN} & \text{\(^{50}\text{Ti}/^{48}\text{Ti}\) in Si/S zone} & \text{\(^{50}\text{Ti}/^{48}\text{Ti}\) in He/C zone} \\
\hline
\text{\(^{28}\text{Si}/^{32}\text{Si}\) in Si/S zone} & \text{\(^{28}\text{Si}/^{32}\text{Si}\) in He/C zone} & \\
\text{\(^{44}\text{Ti}/^{46}\text{Ti}\) in Si/S zone} & \text{\(^{44}\text{Ti}/^{46}\text{Ti}\) in He/C zone} & \\
\hline
\end{array} \]

**Fig. 2.** Plot of 25 M\(_{\odot}\) SNII models vs. different explosion energies in the Si/S and He/C zones.

Since the effect of an increase in the explosion energy can be mimicked by lowering the progenitor mass, the discrepancy likely implies lower progenitor masses for the parent SNII of X grains. We plan to compute new SNII models with a wide range of explosion energies and masses for further investigation. Note that \(^{44}\text{Ti}\) production in the Si/S zone has a much weaker dependence on the explosion energy. The SNII models in Fig. 2 predict \(^{44}\text{Ti}/^{46}\text{Ti}\) of \( \sim 0.6 \) within the constrained explosion energies. This generally agrees with the \(^{44}\text{Ti}/^{46}\text{Ti}\) ratio in the Si/S zone inferred from presolar grains, but there is a large spread in the data [6].

\(^{48}\text{Ti}\) and \(^{50}\text{Ti}\): Figure 2 shows that \(^{48}\text{Ti}/^{50}\text{Ti}\) in the He/C zone decreases with increasing explosion energy, resulting from more efficient neutron-capture in more energetic environments. Previous work observed correlated \(^{48}\text{Ti}\) and \(^{28}\text{Si}\) excesses in X and ungrouped SNII grains, based on which the \(^{48}\text{Ti}/^{50}\text{Ti}\) production ratio was constrained to be unity [4]. Comparison with the model predictions shown in Fig. 2 for Ti isotopes confines the explosion energy to lie within \((1.75-2.00) \times 10^{51} \text{ ergs}\), consistent with the astronomical observations but lower than the constraint obtained for the Si/S zone earlier. The constraint of \((1.75-2.00) \times 10^{51} \text{ ergs}\) is strongly supported by the Mo isotopic pattern observed in X grains [11]. Comparison of Grain B2-05 that had the most extreme isotopic anomalies reported in [11] with the SNII models in Fig. 3 shows that the \(1.75 \times 10^{51} \text{ erg model provides the best match to the grain data, in perfect agreement with the Ti-isotope constraint.} \)

We did not find the formation of Si/C zone (\(^{28}\text{Si}-\text{excess}\)) in our high-energy models as reported in [12]. The difference is likely related to differences in the details of the pre-SN evolutionary simulations adopted in the two sets of models. It was pointed out in [4], however, that the Si/C zone in the model of [12] produces too low Ti that this zone cannot account for the correlated \(28\text{Si}\) and \(49\text{Ti}\) excesses observed in X grains.

**Implications:** The observed Si isotopic compositions of X grains can be explained by SNII nucleosynthesis in the Si/S zone under energetic conditions \((>7 \times 10^{51} \text{ ergs})\). Such high explosion energies are additionally supported by the extremely high \(26\text{Al}/^{27}\text{Al}\) ratios observed in X grains. On the other hand, given the strong dependences of the \(^{49}\text{Ti}/^{50}\text{Ti}\) ratio and the Mo isotopic pattern on the explosion energy, it is clear that X grains were derived from SNII with a narrow range of progenitor masses and explosion energies. Finally, the discrepant explosion energies constrained for the Si/S and He/C zones in this study could be explained if (1) the \(^{22}\text{Ne}(\alpha,\gamma)^{25}\text{Mg}\) reaction rate is lower than currently adopted so that a higher explosion energy is required to produce the same neutron-number density, and/or (2) true hydrodynamical post-shock energy density variations allow the effective explosion energy in the Si/S zone to be higher and that in the He/C zone to be lower than would be inferred from a single explosion energy in the simple models employed here. More work is planned to investigate the two effects in detail.