A NEW METHOD FOR CONSTRAINING EXPLOSIVE ENVIRONMENTS IN TYPE II SUPERNOVAE USING PRESOLAR SILICON CARBIDE X GRAIN ISOTOPIC DATA.

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Introduction: X grains constitute 1−2 % of all presolar SiC found in primitive extraterrestrial materials [1]. The high initial abundances of a number of short-lived nuclides (e.g., ^{26}Al, ^{44}Ti and ^{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 [2]. On the other hand, type C grains and a few ungrouped grains (<0.1 % in population) are probably also sourced from SNII [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 [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 to more material from the Si/S zone [1,2]. **(2)** X grains show ^{44}Ti and ^{49}V excesses that are correlated with their $\delta^{29,30}$Si values, corresponding to positive correlations of ^{44}Ti and ^{49}V with ^{28}Si. The correlations can be used to provide constraints on the production ratios of ^{44}Ti/^{48}Ti in the Si/S zone [6] and ^{49}Ti/^{50}Ti in the He/C zone [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 [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 [7]. For the present study, we computed the explosive nucleosynthesis for an initially 25 $M_\odot$ presupernova model from [8] with explosion energies of (1−10)×10^{51} ergs. In this abstract, by comparing the constrained ^{29}Si/^{30}Si, ^{44}Ti/^{48}Ti, and ^{49}Ti/^{50}Ti ratios with this new set of SNII model calculations, we will provide new insights into the production of Si isotopes and ^{26}Al in SNII and discuss the implications for explosive SNII environments.

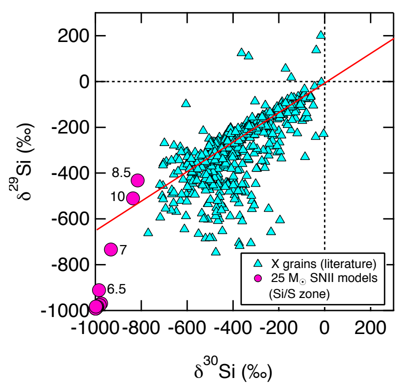

***Fig. 1**. Silicon 3-isotope plot comparing X grains [9] with SNII models. The numbers are the explosion energies (×10^{51} ergs) of the corresponding models.*

^{29}Si/^{30}Si, ^{26}Al and ^{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 (>7×10^{51} ergs) in the center. Figure 2 further illustrates that in such high energy explosions, the Si/S zone produces abundant ^{26}Al with the predicted ^{26}Al/^{27}Al ratios reaching above unity, which can therefore account for the high inferred initial ^{26}Al/^{27}Al ratios (>~0.1 in general) observed in X grains [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 ^{26}Al/^{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 [9]. The inferred explosion energies (>7 ×10^{51} ergs), however, are much higher than those (0.5−3×10^{51} ergs) inferred for a few SNII (10−25 $M_{\odot}$) based on astronomical observations [10].

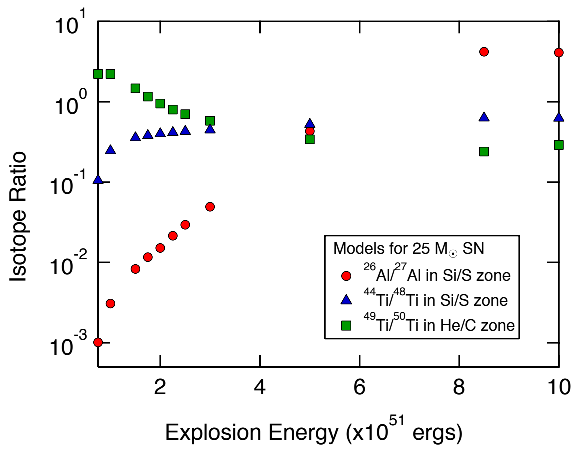

Fig. 2. *Plot of 25 $M_{\odot}$ SNII models vs. different explosion energies in the Si/S and He/C zones.*

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}Ti production in the Si/S zone has a much weaker dependence on the explosion energy. The SNII models in Fig. 2 predict ^{44}Ti/^{48}Ti of ~0.6 within the constrained explosion energies. This generally agrees with the ^{44}Ti/^{48}Ti ratio in the Si/S zone inferred from presolar grains, but there is a large spread in the data [6].

^{49}Ti and ^{50}Ti: Figure 2 shows that ^{49}Ti/^{50}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 ^{49}Ti and ^{28}Si excesses in X and ungrouped SNII grains, based on which the ^{49}Ti/^{50}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)×10^{51} 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)×10^{51} 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 × 10^{51} 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}Si-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}Si and ^{49}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 ×10^{51} ergs). Such high explosion energies are additionally supported by the extremely high ^{26}Al/^{27}Al ratios observed in X grains. On the other hand, given the strong dependences of the ^{49}Ti/^{50}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}Ne(α,n)^{25}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.

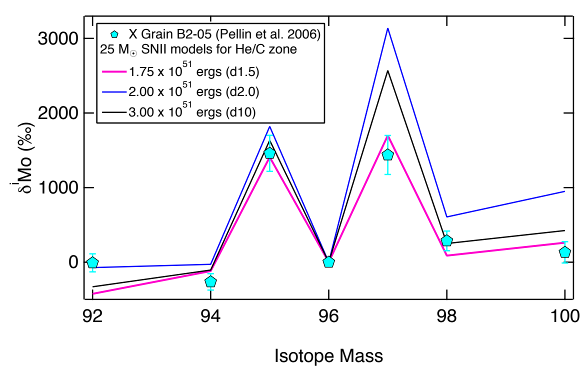

Fig. 3. *Mo isotope plot comparing an X grain in [11] with 25 $M_{\odot}$ SNII models. The model predictions are scaled down to the match the grain for δ^{95}Mo, and the scale factors are in the parentheses in figure caption.*

References: [1] Nittler L. R. and Ciesla F. (2016) *ARA&A, 54,* 53–93. [2] Nittler L. R. et al. (1996) *ApJ, 462,* L31. [3] Pignatari M. et al. (2013) *ApJL*, *771*, L7. [4] Liu N. et al. (2018) *Sci. Adv.*, *4*, eaao1054. [5] Pignatari M. et al. (2015) *ApJL*, *808*, L43. [6] Gyngard F. et al. (2018) *GCA*, *221*, 60–86. [7] Bojazi M. J. and Meyer B. S. (2014) *PhRvC*, *89*, 025807. [8] Rauscher T. et al. (2002) *ApJ*, *576*, 323. [9] Stephan T. et al. (2020) *LPS LI*, this meeting. [10] Bruenn S. W. et al. (2016) *ApJ*, *818*, 123. [12] Pellin M. J. et al. 2006, *LPS XXXVII*, Abstract #2041. [12] Pignatari et al. (2013) *APJL*, *767*, L22.