PRODUCTION OF NITROGEN-15 IN EXPLOSIVE HELIUM BURNING AND SUPERNOVA PRESOLAR GRAINS.

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Introduction: Presolar grains from supernovae provide important constraints on stellar explosions through their isotopic signatures. To explore these constraints, one typically compares the grain data to output from detailed supernova models, for example, those of Rauscher et al. [1]. In order to match the grain isotopic data, it appears that widely separated layers of the supernova ejecta must mix at the microscopic level prior to or during grain formation (e.g., [2]).

Ejecta mixing models can explain much of the isotopic data in supernova grains, but many puzzles remain. For example, the grains are ^{15}N rich compared to solar, but not all stellar models yield the necessary ^{15}N excesses (e.g., [3]). To help resolve some of these puzzles, we have begun a systematic study of the explosive nucleosynthesis in supernovae to understand the formation of the key nuclear species for the supernova grains. This will help clarify the sensitivity of the production to supernova explosion parameters and to key reactions whose rates may be uncertain. Instead of taking a presupernova model and applying an explosion code, we simply run a constant Mach Number shock through the model and follow the resulting nucleosynthesis. This allows us to explore conditions that might not be found in the more detailed models. In this abstract, we focus in particular on nitrogen.

The Calculations: To study the sensitivity of supernova yields to the peak temperature and density in the supernova explosion, we developed a network code based on libnucnet, a C toolkit for storing and managing nuclear reaction networks [4]. This code read in the presupernova structure and composition files for model s15a28, an originally 15 solar mass star evolved to the point of core collapse by Rauscher et al. [1]. We then imagined a supernova shock of constant Mach number passing through the star. For each zone in the presupernova model, we computed the post-shock temperature and density from the Rankine-Hugoniot relations. We then allowed each zone to expand and cool on a hydrodynamical timescale (in seconds) $\tau = 446 / \rho_0^{1/2,}$ where ρ_0 is the post-shock density. We then evolved the abundances from their initial presupernova values using reaction rates from the reaclib data base [5]. Our calculations did not include the effects of supernova neutrinos. We followed the explosive nucleosynthesis until the material had cooled to a temperature below 10^5 K, by which time strong and electromagnetic reactions had ceased and only beta decays could subsequently change the abundances.

Nitrogen Production: Assuming the pre-shock gas is monatomic and non-relativistic, we can take the adiabatic index γ=5/3. For Mach number 1, then, the pre-shock and post-shock temperature and densities are the same. For a Mach 2 shock, the post-shock temperature and density are both approximately twice as large as their pre-shock values. For Mach 3, the post-shock temperature is about four times its pre-shock value while the post-shock density is approximately three times its pre-shock value.

Figure 1 shows the final explosive mass fraction of ^{15}N as a function of interior mass coordinate for several Mach numbers. Since the expansion timescale is rapid, even for the Mach 1 shock, the abundances are little changed from their presupernova values; thus, the Mach 1 mass fractions show, to good approximation, the presupernova ^{15}N mass fraction. As the Mach number of the shock increases, the post-shock temperature and density increase, which leads to a greater degree of explosive nucleosynthesis. This is evident in Figure 1 as increasing the Mach number of the shock from 1.5 to 2.5 increases the ^{15}N mass fraction near M_r = 3 solar masses. At Mach number 3, the peak in the ^{15}N moves out to $M_r \approx 3.2$ solar masses.

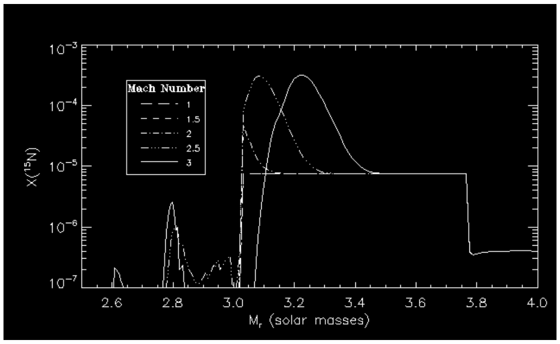

Fig. 1: Final ^{15}N mass fraction in the originally 15 solar mass model as a function of interior mass coordinate M_r for the indicated shock Mach Numbers.

The presupernova helium burning shell for this model stretches from M_r = 3 to about 3.8 solar masses. This shell in the star is abundant in ^{4}He and ^{14}N. It is also abundant in ^{22}Ne, which was produced by partial helium burning of the ^{14}N during presupernova evolution. The reaction sequence is $^{14}N(\alpha,\gamma)^{18}F$, $^{18}F \rightarrow {}^{18}O$ (beta decay), $^{18}O(\alpha,\gamma)^{22}Ne$.

When the shock passes through the helium burning shell, the $^{14}N(\alpha,\gamma)^{18}F$ reaction still occurs rapidly. The ^{18}F beta decay timescale, however, is long (~110 minutes) compared to the expansion timescale. At the same time, neutrons are liberated by the reaction $^{22}Ne(\alpha,n)^{25}Mg$. The ^{18}F then undergoes the $^{18}F(n,\alpha)^{15}N$ reaction. The ^{15}N thus produced can then capture ^{4}He and be destroyed, but if the expansion is rapid enough, the destruction of nitrogen terminates and leaves a significant abundance of ^{15}N.

Also contributing to the ^{15}N abundance is the reaction $^{18}O(p,\alpha)^{15}N$. This ^{18}O is both from the presupernova model and from ^{18}F via $^{18}F(n,p)^{18}O$. The (p,α) production of ^{15}N occurs somewhat later in the explosive burning once the abundance of protons builds up by (n,p) reactions on nuclei. Direct production of ^{15}N by $^{14}N(n,\gamma)^{15}N$ is not significant because the cross section for this reaction is much smaller than the (n,α) cross sections on ^{18}F. A 100-fold increase in the $^{14}N(n,\gamma)^{15}N$ cross section, with all other quantities the same, increases the ^{15}N yield by only 13% for the Mach 3 case.

We may now understand the details of Figure 1. For Mach number 1 or 1.5, the shock-induced nucleosynthesis is not significant in the helium burning shell. At Mach number 2, the post-shock temperature and density in the innermost part of the helium shell gets large enough to produce some ^{15}N. At larger M_r, however, the post-shock temperature and density are too small to lead to much ^{15}N production. At Mach number 2.5, there is significant production of ^{15}N with a peak near a mass fraction of about 4×10^{-4}. At the still larger Mach number of 3, the peak in the ^{15}N production moves out to larger M_r because the inner zones have been heated and compressed to large enough values the the newly produced ^{15}N is subsequently destroyed.

It is interesting that the peak ^{15}N mass fraction is about the same for the Mach 2.5 and 3 cases. The ^{15}N production is a balance between production from ^{14}N and ^{18}O and destruction by capture of ^{4}He. Since the presupernova ^{14}N and ^{18}O abundances are uniform in the helium shell, increasing the shock strength simply moves the peak in the ^{15}N outwards in the shell but does not increase its value.

Figure 2 shows the post-supernova mass fractions of ^{14}N and ^{15}N for the Mach 3 case. Since there is little nitrogen inside $M_r = 2$ solar masses and the mass fractions of the nitrogen isotopes are uniform outside of $M_r = 4.3$ solar masses, the peak in the ^{15}N mass fraction near $M_r \approx 3.2$ solar masses is by far the most ^{15}N-rich zone in the star. The $^{14}N/^{15}N$ ratio at the peak is 8.3, which is ~33x the solar ratio. Below $M_r \approx 3.2$ solar masses, the $^{14}N/^{15}N$ can be even smaller (near unity), though the nitrogen abundance is also low.

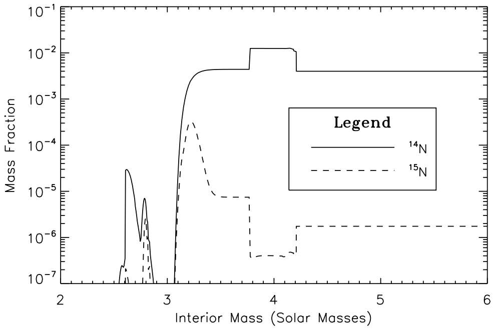

Fig. 2: Final ^{14}N and ^{15}N mass fractions in the originally 15 solar mass model as a function of interior mass coordinate M_r for the Mach 3 shock.

Implications for Supernova Grains: Presolar SiC grains show high inferred $^{26}Al/^{27}Al$ ratios. This suggests that helium shell material must mix with matter from the He/N region of the star (e.g., [2]). This material, however, typically has a large $^{14}N/^{15}N$ ratio. The mixtures needed to match supernova SiC grain carbon and isotopic signatures do not typically work [2]. The initially 25 solar mass model that Lin et al. [2] consider only works when He/N material centered on a ^{15}N-rich spike is included. The origin of this spike is not well understood, and it does not show up in other models.

The results of the present study suggest how one might improve the C-N abundance match to the grains. In the absence of neutrinos, ^{15}N is produced by alpha and neutron capture sequences discussed above. Increasing the shock speed through the helium-rich (He/C) zone will increase the ^{15}N abundance. As seen in Figure 1, however, there is a limit to the ^{15}N production because of the balance between production and destruction and the supply of initial ^{14}N. It may also be that the key alpha and neutron capture rates are uncertain and a change in one or more of the rates may change the ^{15}N yield. For example, for the peak case for Mach 3, a 100-fold increase in the rate for $^{18}F(n,\alpha)^{15}N$ increases the ^{15}N yield by a factor of ~2.2. It will be interesting to see if new explosion models or improved reaction rates increase ^{15}N production as we here envision and provide a better match to grain data.

References: [1] Rauscher T. et al. (2002) *ApJ, 576*, 323-348. [2] Lin Y. et al. (2010) *ApJ*, *709*, 1157-1173. [3] Limongi M. and Chieffi A. (2006) *ApJ*, *647*, 483-500. [4] Meyer B. S. and Adams D. C. (2007) *Meteoritics & Planet. Sci., 42, A5215.* [5] Cyburt R. H. et al. (2010) *ApJS, 189,* 240-252. [6] Lodders K. (2003) *ApJ*, *591*, 1220-1247.