On the Site of the Weak r-Process Component*

James W. Truran[1] and John J. Cowan[2]

[1] Department of Astronomy and Astrophysics, Enrico Fermi Institute, University of Chicago, Chicago, IL, 60637
[2] Department of Physics and Astronomy, University of Oklahoma, Norman, OK, 73019

Abstract. There is increasingly strong observational evidence that the r-process isotopes identified in solar system matter are in fact the products of two distinct classes of r-process events. The r-process abundance pattern in the mass range A $\gtrsim$ 130-140, the signature of which is unambiguously imprinted upon the abundance patterns of the most metal deficient halo field stars, are generally assumed to have been synthesized in an environment tied to massive stars (M $\gtrsim$ 10 $M_\odot$) and associated Type II supernovae. Observations both of the oldest stars and of the abundances of short lived radioactivities in primordial solar system matter indicate, however, that a second r-process nucleosynthesis site is necessary to explain the abundances of the r-process nuclei in the range A $\lesssim$ 130-140. We present preliminary calculations which suggest that this site may be associated with the shock processing of the helium and/or carbon shells of Type II supernovae.

1 Introduction

While the general nature of the r-process and its contributions to the abundances of heavy elements in the mass range through uranium and thorium are generally understood, the details remain to be worked out. There are considerable uncertainties associated both with the basic nuclear physics of the r-process - which involves the neutron-capture, beta-decay, and fission properties of unstable nuclear species far from the region of β-stability - and with the characteristics of the stellar or supernova environments in which r-process synthesis occurs. Until recently, it was at least reassuring that, in contrast to s-process, it appeared a single r-process site was involved. Observations reviewed in the next section now suggest that this is not true - rather, there must be distinct classes of r-process events operating in the mass regimes above and below masses A $\approx$ 130-140. These abundance clues will be briefly discussed in the next section.

We report here exploratory calculations of the consequences of r-process synthesis in helium shells of Type II supernovae. We begin with the assumption that the site of operation of the main r-process component is not in these helium shells but rather occurs elsewhere (e.g. outside the neutronized core,

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in magnetic jets from the collapsing core, or in neutron-star mergers, ...). We then ask what the helium and carbon shells might be able to contribute to r-process nucleosynthesis. We feel confident that the temperature/density conditions to which the helium and carbon rich regions of massive stars (M $\gtrsim$ 10 $M_{\odot}$) will be subjected in the wake of the outgoing shock will yield some r-process nuclei. Can this environment be responsible for the entire weak r-process component, does it contribute significantly to the some of the r-process anomalies identified in presolar grains, is its level of activity in the oldest stars consistent with the observed abundances of the light n-capture elements in low metallicity stars? We first review current theoretical models for the production of the main r-process component (A $\gtrsim$ 130-140) and then present calculations relevant to the synthesis of the lighter r-process elements.

2 Abundance Clues to r-Process Synthesis Sites

r-Process abundances in low metal stars provide several important clues to the nature of the r-process site:

- r-Process synthesis of A $\gtrsim$ 130-140 isotopes happens early in Galactic history [1], prior to input from AGB stars to the abundances of heavy s-process isotopes.
- The r-process mechanism for the synthesis of the A $\gtrsim$ 130-140 isotopes (which we will refer to as the 'main' component) is extremely robust. This is reflected in the fact that the abundance patterns in the most metal deficient (oldest) stars, which may have received contributions from only one or a few r-process events, are nevertheless entirely consistent with the r-process abundance pattern which characterizes solar system matter. (The abundance patterns for the two stars CS 22892-052 [2,3] and HD 115444 [4,5] shown in Figure 2 of the Cowan, Truran, & Sneden [6] paper in these proceedings reveal this remarkable agreement for two stars of low metallicity but high [r-Process/Fe].)
- Of relevance to our discussion in this paper, the abundance pattern in the mass regime below A $\approx$ 130 does not exhibit this consistency [6]. It is the source of these lighter r-nuclei (the 'weak' component) that we seek to identify in this paper.

It is also interesting to note that there exists evidence for a second, weak r-process component from another source. Wasserburg, Busso, & Gallino [7] have pointed out that the abundance levels of the short-lived isotopes ^{107}Pd and ^{129}I in primordial solar system matter are inconsistent with their having been formed in uniform production together with the heavy r-process radioactivities (specifically, ^{182}Hf, ^{235}U, ^{238}U and ^{232}Th). They suggest that these two different mass ranges of nuclei require different timescales for production and therefore suggest two distinct r-process sites. This seems entirely compatible with the weak (A $\leq$ 130-140) and main (A $\geq$ 130-140) r-process components as we have identified them above.

3 r-Process in Helium/Carbon Shells in Type II Supernovae

The appearance of r-process nuclei in the oldest known stars in our Galaxy strongly suggests the identification of the site of the main r-process component (A $\gtrsim$ 130-140) with massive stars and associated Type II supernova environments. We note that the three mechanisms currently considered for the r-process are all associated in some way with this environment. This includes nucleosynthesis associated with: (i) neutrino-driven winds from forming neutron stars [8,9]; (ii) neutron star mergers [10,11]; and (iii) magnetic jets from collapsing stellar cores [12].

An alternative possible site for r-process synthesis is that associated with the helium and carbon shells of massive stars undergoing supernovae [13–15]. Shock processing of these regions can give rise to significant neutron production via such reactions as $^{13}C(\alpha,n)^{16}O$, $^{18}O(\alpha,n)^{21}Ne$, and $^{22}Ne(\alpha,n)^{25}Mg$, involving residues of hydrostatic burning phases. The early studies cited above were motivated by the desire to produce the entire range of r-process nuclei through uranium and thorium. It was found, however, that this could be accomplished only with the use of excessive and quite unrealistic concentrations of e.g. ^{13}C [16].

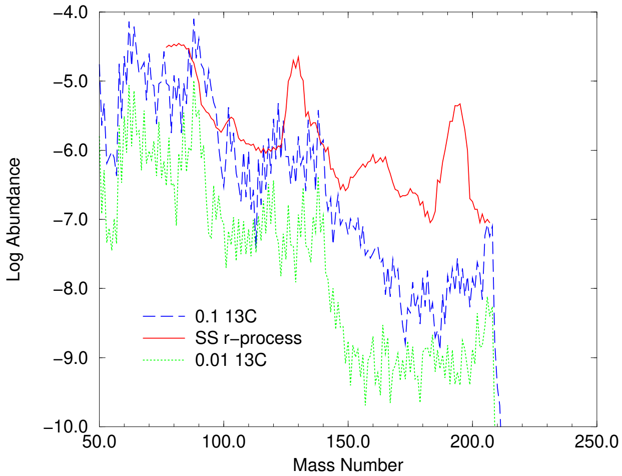

Fig. 1. The r-process abundance patterns resulting from two representative ^{13}C(α,n)^{16}O neutron exposures in the helium shell of a massive star are compared with the solar system r-process abundance distribution (solid line).

The observational and theoretical considerations discussed previously serve to ease these demands: we need now only to be able to produce the r-process nuclei in the mass range through A $\approx$ 130-140. Guided by stellar models for massive stars at the end of their hydrostatic evolution [17], we have calculated the r-process history of matter processed through the shock heated helium shell for two choices of the initial abundance of ^{13}C: X_{13}=0.1 and 0.01. The initial (post shock) temperature and density were taken to be 7x10^8 ^{o}K and 10^4 g/cc, respectively. Here we have assumed an active $^{13}C(\alpha,n)^{16}O$ neutron source acting on a preexisting solar abundance pattern as seed nuclei, and calculated nucleosynthesis occurring on an expansion time scale. (We note that we might also expect important contributions from the $^{18}O(\alpha, n)^{21}Ne$ and $^{22}Ne(\alpha, n)^{25}Mg$ reactions.) The results are displayed in Figure 1, where the calculated abundance patterns for the two choices of X_{13} are compared with the solar system r-process pattern. We note that for the more realistic case of X_{13}=0.01, the element abundance enrichments fall sharply in the range A $\gtrsim$ 130. The r-process products are thus confined to the light mass region that seems not to receive significant contributions from the main r-process component.

4 Conclusions

Our results confirm that the helium and carbon layers of massive stars, when subjected to outgoing shocks characteristic of Type II supernovae, can represent an important nucleosynthesis site - specifically for the light r-process nuclei. The great sensitivity to conditions of temperature, density, and initial composition that we have found in our exploratory survey strongly suggest that this r-process mechanism will prove less robust in its ability to reproduce the observed r-process pattern in the mass range A $\lesssim$ 130-140.

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