Halo Star Abundances and r-Process Synthesis

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The heavy elements formed by neutron capture processes have an interesting history from which we can extract useful clues to and constraints upon the star formation and nucleosynthesis history of Galactic matter. Of particular interest are the heavy element compositions of extremely metal-deficient stars. At metallicities [Fe/H] $\leq$ -2.5, stellar abundance data (for both halo field stars and globular cluster stars) provides strong confirmation of the occurrence of a robust r-process mechanism for the production of the main r-process component, at mass numbers A $\gtrsim$ 130-140. The identification of an environment provided by massive stars and associated Type II supernovae as an r-process site seems compelling. Scatter in the ratio [r-process/Fe] provides a measure of the level of inhomogeneity characteristic of the halo gas at that early epoch. Increasing levels of s-process enrichment with increasing metallicity reflect the delayed contributions from the intermediate mass stars that provide the site for s-process nucleosynthesis during the AGB phase of their evolution. For the mass region A $\lesssim$ 130, the abundance patterns in even the most metal deficient stars are not consistent with the solar system r-process abundance distribution, providing evidence for the fact that the r-process isotopes identified in solar system matter are in fact the products of two distinct r-processes nucleosynthesis events. We review recent observational studies of heavy element abundances in low metallicity stars and explore some implications of these results for nucleosynthesis and early Galactic chemical evolution.

1. INTRODUCTION

Element abundance patterns in very metal-poor halo field stars and globular cluster stars play a crucial role in guiding and constraining theoretical models of nucleosynthesis [1, 2]. Nowhere is this more true than for the case of the neutron-capture processes that are understood to be responsible for the synthesis of the bulk of the heavy elements in the mass region A $\gtrsim$ 60: the s-process and the r-process. Nucleosynthesis theory identifies quite different astrophysical sites for these two distinct processes. r-Process nuclei (at least the heavy (A $\gtrsim$ 140) r-process isotopes) are *primary* nucleosynthesis products, presumed to have been formed in an environment associated with the evolution of massive

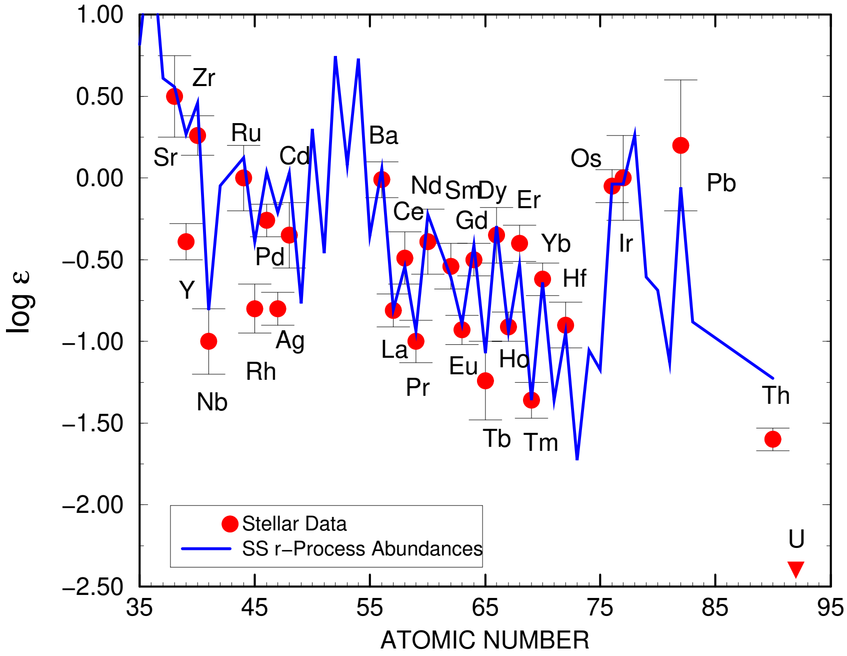

Figure 1. The heavy element abundance patterns for CS 22892-052 compared with the solar system r-process abundance distribution (solid line) [7]

stars (M $\gtrsim$ 10 $M_\odot$) to supernova explosions of Type II and the formation of neutron star remnants. s-Process nuclei are understood to be products of neutron captures on preexisting silicon-iron “seed” nuclei, occurring both in the helium burning cores of massive stars and particularly in the thermally pulsing helium shells of asymptotic giant branch (AGB) stars. In this picture, the first heavy (A $\gtrsim$ 60) elements introduced into the interstellar gas component of our Galaxy are expected to have been r-process nuclei formed in association with massive stars, on timescales $\tau_* < 10^8$ years [3].

That the general features of this simple model are correct is confirmed by the finding that r-process contributions dominate the heavy element abundances in extremely metal-poor halo stars. This issue is discussed in the next section. The implications of trends in the heavy element abundances as a function of [Fe/H] for the early star formation history of the Galaxy and Galactic chemical evolution are then examined. The interpretation of the observed trends in [Ba/Eu] in the context of models of Galactic chemical evolution is discussed in section 3. The implications of the increasingly pronounced scatter in the ratio of the abundance of r-process nuclei to iron [r-process/Fe] with decreasing metallicity are explored in section 4. Evidence of and a possible model for a second (weak) r-process nucleosynthesis event [4] are discussed in section 5. Discussion and conclusions follow.

2. R-PROCESS ABUNDANCES IN METAL-POOR HALO STARS

Significant progress in our understanding of the site of operation of r-process nucleosynthesis has followed from studies of the abundances of elements from barium through

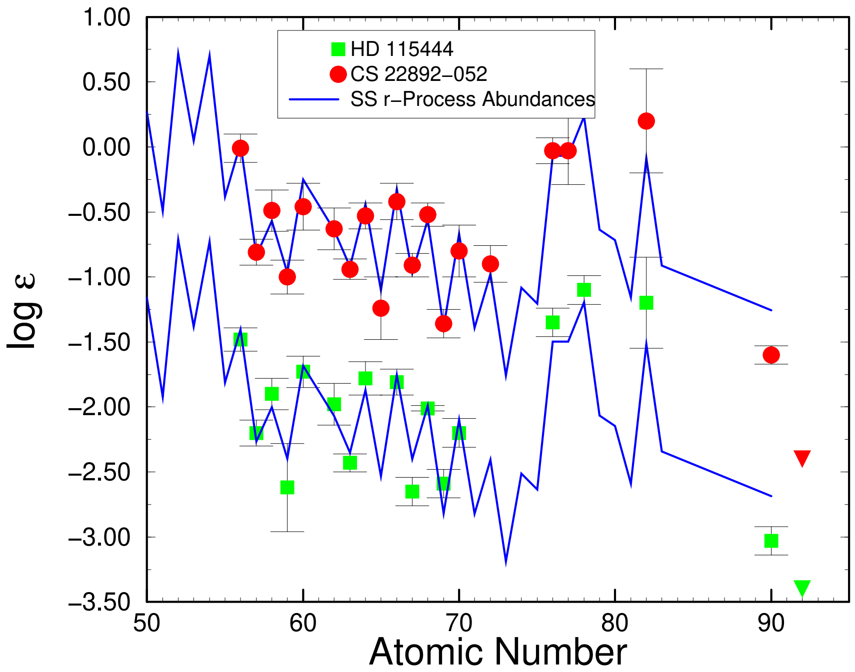

Figure 2. The heavy element abundance patterns for the two stars CS 22892-052 and HD 115444 are compared with the solar system r-process abundance distribution (solid lines) [7,11]

bismuth in metal-poor stars. Both ground-based [5–8] and space based [9,10] observational studies have confirmed that the abundances of the heavy neutron-capture products (A $\gtrsim$ 130-140) in the most metal deficient halo field stars and globular cluster stars ([Fe/H] $\lesssim$ -2.5) were formed in a robust r-process event. This is most clearly reflected in the abundance pattern for the ultra metal poor ([Fe/H] = -3.1), but r-process enriched ([r-process/Fe] $\approx$ 30-50), halo star CS 22892-052 [5,7] shown in Figure 1. Note the truly remarkable agreement of the elemental abundance pattern in the region from barium through bismuth with the solar system elemental pattern.

It is also important to recognize that this detailed level of agreement of the metal-poor star heavy element abundance pattern with (solar system) r-process abundances is a feature of all studied stars of [Fe/H] $\lesssim$ -2.5. The heavy element abundance patterns for the two stars CS 22892-052 [5,7] and HD 115444 [11] are compared with the solar system r-process abundances in Figure 2.

The robustness of the r-process mechanism operating in the early Galaxy is reflected in the close agreement of these two stellar patterns (which represent the nucleosynthesis products of, at most, a relatively small number of earlier stars) with the solar system r-process pattern (which represents the accumulated production of r-process elements over billions of years of Galactic evolution). Note the extraordinary agreement with solar system r-process abundances over this range, for the eighteen elements for which abundance data is available. These data provide conclusive evidence for the operation of

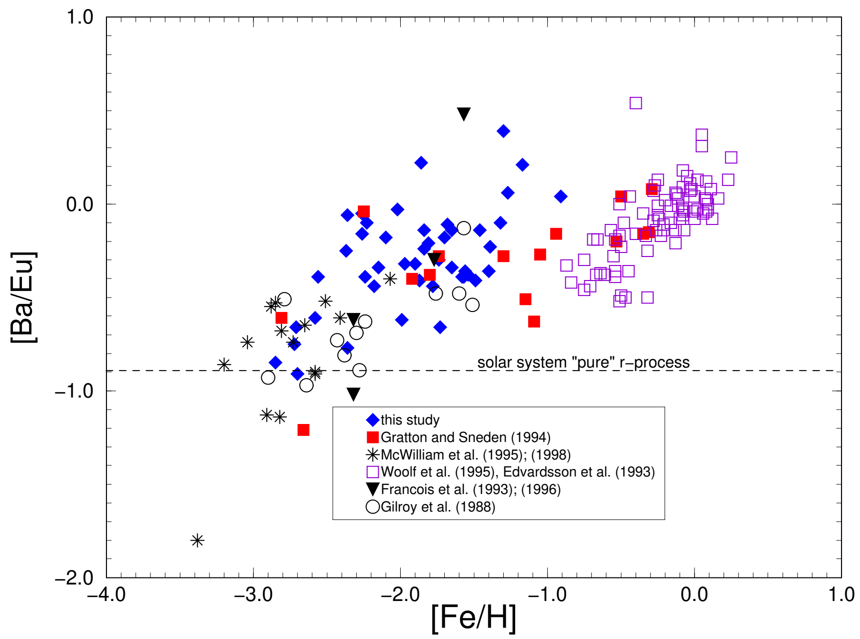

Figure 3. The ratio [Ba/Eu], which reflects the ratio of s-process to r-process elemental abundances, is displayed as a function of [Fe/H] for a large sample of halo and disk stars [8]

an r-process at the earliest Galactic epochs that synthesizes the heavy r-process nuclei (barium and beyond), including the long lived isotope ^{232}Th critical to dating. The identification with massive stars seems compelling, although it is possible that neutron star mergers rather than a supernova environment may be responsible.

3. CHEMICAL EVOLUTION OF R-PROCESS AND S-PROCESS ABUNDANCES

Studies of the time history of the heavy (neutron capture) elements have historically been driven by observations. Early trends in the s-process element patterns as a function of [Fe/H], noted by Pagel [12], motivated theoretical consideration of such trends in the context of models of Galactic chemical evolution [13]. The great increase in abundance data for metal-poor stars over the past decade has similarly motivated considerable theoretical activity [14–16]. The ratio [Ba/Eu], which reflects the ratio of s-process to r-process elemental abundances, is displayed in Figure 3 as a function of [Fe/H], for a large sample of halo and disk stars from the survey by Burris *et al.* [8]. Note that at the lowest metallicities the [Ba/Eu] ratio is consistent with that for pure r-process matter. The subsequent increase in the [Ba/Eu] ratio with increasing [Fe/H] (i.e. increasing time) to its solar value reflects the input to the interstellar medium of the products of s-process nucleosynthesis in intermediate mass stars of lifetimes greater than those of the massive star sites of r-process nucleosynthesis. This data provides important clues to the history of s-process and r-process nucleosynthesis over the course of Galactic evolution.

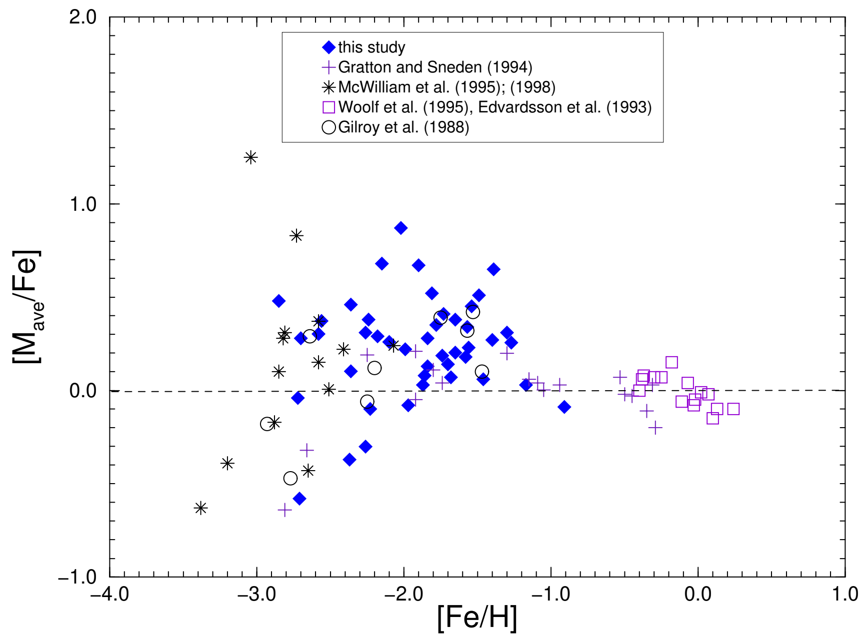

Figure 4. The ratio [r-process/Fe] is displayed as a function of [Fe/H] for a large sample of halo and disk stars [8]

4. IMPLICATIONS OF SCATTER IN [r-Process/Fe]

r-Process abundances in low metal stars also provide an important further clue to the nature of the r-process site. The ratio [r-process/Fe] is displayed as a function of [Fe/H] for a large sample of halo and disk stars [8] in Figure 4. The increasing level of scatter of this ratio with decreasing metallicity, most pronounced at values below [Fe/H] $\sim$ -2.0, makes clear that not all early stars are sites for the formation of both r-process nuclei and iron. In the absence of other sources for either iron peak nuclei or r-process nuclei in the early Galaxy, this scatter is consistent with the view that the r-process operates in only a small fraction ($\sim$ 1/10th to 1/50th) of the massive stars that produce iron [17]. Note again that this refers *only* to the nucleosynthesis sites for the heavy r-process isotopes (barium and beyond), and not to any possible site for the production of the lighter r-process nuclei.

The scatter in the r/Fe trend is itself interesting and can teach us much about the formation of the first supernovae and their spatially *inhomogeneous* enrichment of the halo stars. The scatter has been studies in detailed models, by Ishimaru & Wanajo [18], Raiteri et al. [19], and Argast et al. [20]. The essence of what is going on is captured in a simple, stripped-down model we have constructed for the enrichment of the halo stars.

The r-process abundance data in extremely metal poor (i.e., low [Fe/H]) stars drives the model assumptions in a fairly direct manner. Namely, (1) from low metallicity of [Fe/H] ~ -3 or less, we conclude that each star samples only a few (perhaps only one or two?) nucleosynthesis events (Audouze & Silk [21]; see also Wasserburg, these proceedings). (2) The low metallicities also imply short-lived progenitors of both the Fe and r-process observed; we will refer to these progenitors as supernovae, though NS-NS binaries are also possible [22]. (3) From the large scatter in observed r/Fe, we infer that not all supernovae make both the (heavy) r-process and iron. (4) Finally, from the stunningly solar ratios *among* the different r-process elements within single stars (see, e.g., our Figure 2), we conclude that the r-process is *universal*–i.e., the events that produce the r-process always closely reproduce the solar system r-process pattern.

We therefore posit that there are two populations of supernovae, one of which yields mostly the heavy (A $\gtrsim$ 140) r-process isotopes (more specifically, a high r/Fe ratio), while the other yields iron (i.e., a low r/Fe). The r/Fe yield of each population is a parameter, but is constrained by the data which sets a lower limit on $(r/\mathrm{Fe})_{\mathrm{high}}$, and an upper limit on $(r/\mathrm{Fe})_{\mathrm{low}}$. Furthermore, an additional and key constraint comes from the fact that, averaged over many events of both types, the final r/Fe ratio has to be that which is observed at [Fe/H] = -1 (the highest metallicity at which Fe is not contaminated by Type Ia supernova debris). This ratio, $(r/\mathrm{Fe})_{\mathrm{avg}} \simeq 3(r/\mathrm{Fe})_{\odot}$ sets the fraction f of high r/Fe events, since $r/\mathrm{Fe}_{\mathrm{avg}} = f(r/\mathrm{Fe})_{\mathrm{high}} + (1-f)(r/\mathrm{Fe})_{\mathrm{low}}$. Also, for simplicity we assume that each supernovae of either population produces the same iron yield.

Our model then consists of a Monte-Carlo simulation of halo-star enrichment by supernovae. For each star, we impose a total number N of supernova ancestors; this fixes the [Fe/H] for the star. Of these, the numbers of high and low r/Fe progenitors are taken to be random variables. This is meant to encode the stochastic and inhomogeneous nature of the halo. Thus, a star's supernova antecedents are chosen from a binomial distribution, whose means are the expected values fN and $(1-f)N$; this fixes r/Fe for the star. The Poisson noise in the high/low ancestry leads to scatter in r/Fe, which scales as $1/\sqrt{N} \propto 1/\sqrt{\mathrm{Fe/H}}$ and thus increases with decreasing Fe/H, as observed. The results of a typical run are shown in Figure 5, which also shows the observed scatter. We see that this very simple model nicely accounts for the scatter simply by allowing for stochastic, inhomogeneous mixing of the r-process and iron from two populations.

5. EVIDENCE FOR AND A MODEL FOR A SECOND R-PROCESS EVENT

Recently, Sneden *et al.* [7] obtained detections of six new elements in the relatively unexplored elemental regime from Z = 41–48 in CS 22892–052. These data are displayed in our Figure 1. Note particularly that the close agreement of the abundance pattern for the heavier n-capture elements with the solar system r-process pattern does not extend to the lighter elements, *e.g. the region below Ba.* This suggests that, perhaps, a second r-process site may be required.

It is also interesting to note that there exists evidence for a second, weak r-process component from another source. Wasserburg, Busso, & Gallino [23] 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.

The appearance of r-process nuclei in the oldest known stars in our Galaxy strongly

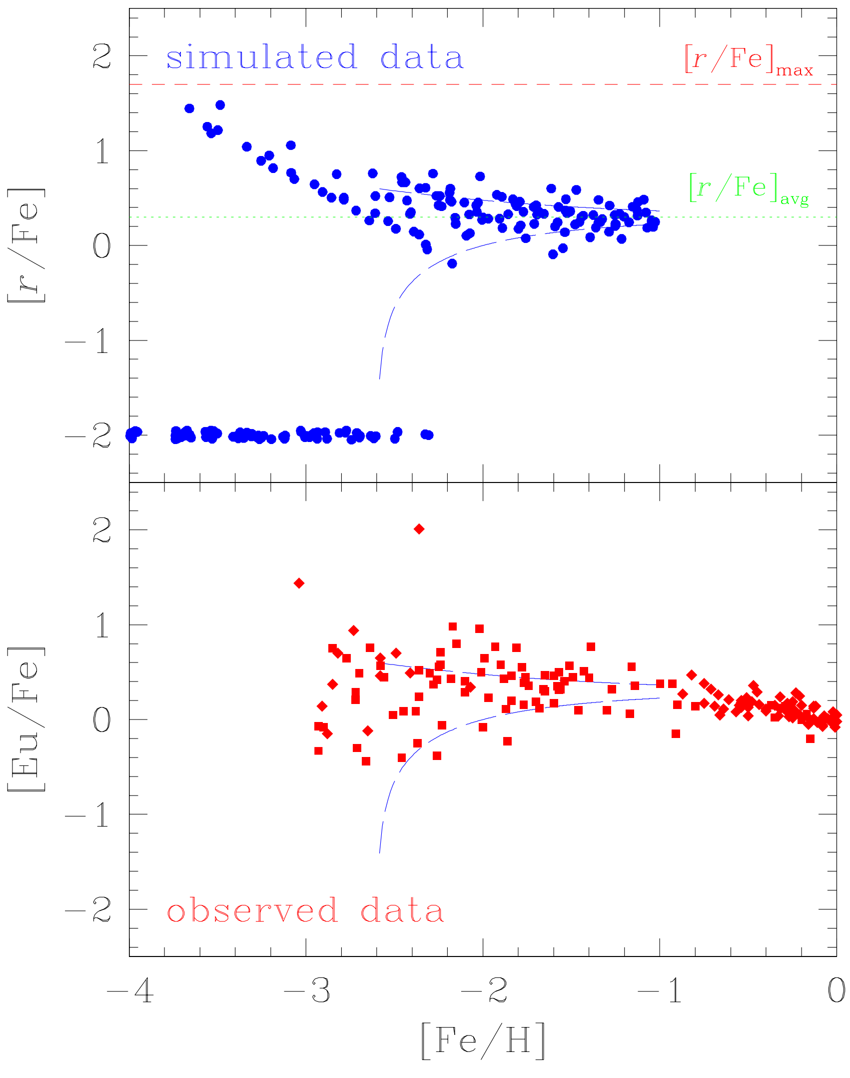

Figure 5. Ratios r/Fe as a function of iron abundance. *Upper panel*: Monte Carlo simulation, upper limits indicated as points at [r/Fe] = -2. *Lower panel*: observed data. In both cases, the dashed curves indicate the model prediction of the 1-σ envelope in the scatter.

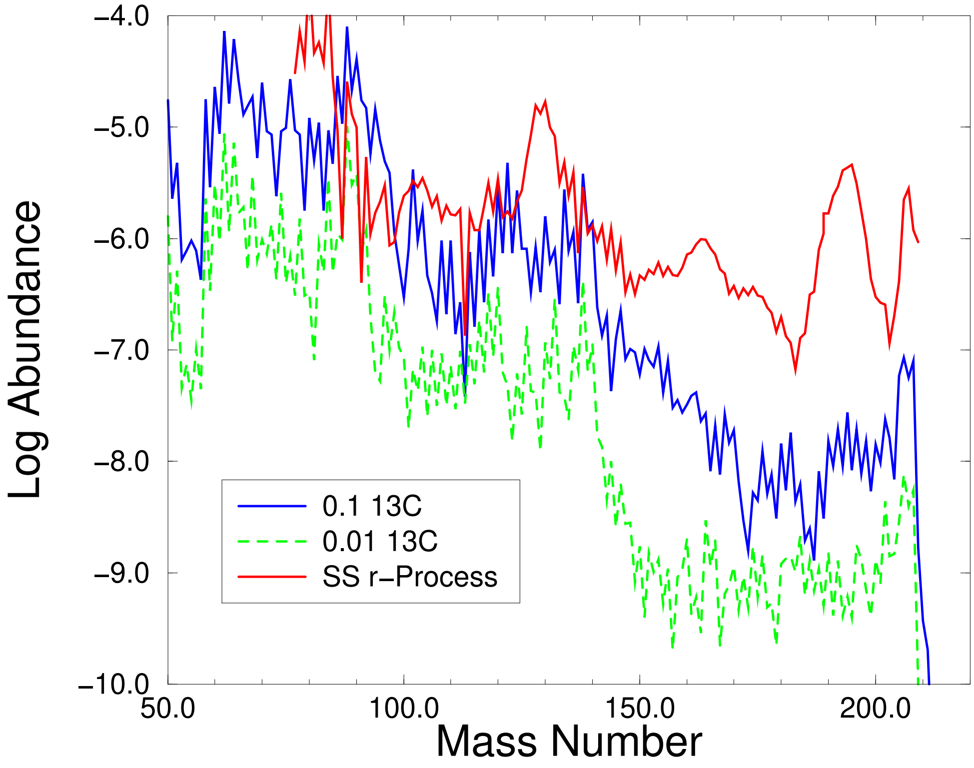

Figure 6. The r-process abundance patterns resulting from two representative ^{13}C(α,n)^{16}O neutron exposures in the helium shell of a massive star are compared with the solar system r-process abundance distribution (solid line).

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 [24,25]; (ii) neutron star mergers [26,27]; and (iii) magnetic jets from collapsing stellar cores [28].

An alternative possible site for r-process synthesis is that associated with the helium and carbon shells of massive stars undergoing supernovae [29–31]. 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 [32].

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 [33], 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 6, 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 formed under these conditions are thus confined to the light mass region that seems not to receive significant contributions from the main r-process component.

6. DISCUSSION AND CONCLUSIONS

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 [3], prior to input from AGB stars to the abundances of heavy s-process isotopes.

- The chemical evolution of the main sources of s-process and r-process nuclei is reflected in the evolution of [Ba/Eu] with respect to [Fe/H], shown in Figure 3 [8]. The stellar data indicate that, at metallicities [Fe/H] $\lesssim$ -2.5, the abundance pattern of the heavy *n*-capture products is consistent with purely *r*-process nucleosynthesis production. *s*-process contributions are first seen in some stars at metallicities as low as [Fe/H] $\sim$ -2.75, and are observed in most stars with metallicities [Fe/H] $>$ -2.3. This identifies the delayed entry of Ba from the low mass AGB stars that represent the site of operation of the main *s*-process component, on a timescale $\sim$ 10^9 years.

- The observed scatter in the ratio [r-Process/Fe] is quite large at low metallicities [8], while at high metallicities it essentially disappears. We have shown that this behavior can be understood as a reflection of the increasing level of inhomogeneity of Galactic matter at earlier epochs.

- 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 [5,7] and HD 115444 [11] shown in Figure 2 reveal this remarkable agreement for two stars of low metallicity but high [r-Process/Fe].)

- The abundance pattern in the mass regime below A $\approx$ 130 does not exhibit this consistency. It is the source of these lighter r-nuclei (the 'weak' component) that we have sought to identify in our very preliminary survey of r-process nucleosynthesis conditions in the helium and carbon shells of Type II supernovae [4].

- Our numerical 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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REFERENCES

1. Wheeler, J. C., Sneden, C., &Truran, J. W. (1989) ARA&A **27**, 279.
2. McWilliam, A. (1995) ARA&A, **35**, 503.
3. Truran, J.W. (1981) A&A **97**, 391.
4. Truran, J.W. & Cowan, J.J. (2000) in *Proceedings of the 10th Ringberg Workshop on Nuclear Astrophysics*, Max-Planck-Institute for Astrophysics, Publication P12, p. 64.
5. Sneden, C., McWilliam, A., Preston, G.W., Cowan, J.J., Burris, D.L., & Armosky, B.J. (1996) ApJ **467**, 819.
6. McWilliam, A. (1998) AJ, **115**, 1640.
7. Sneden, C., Cowan, J.J., Ivans, I. I., Fuller, G. M., Burles, S., Beers, T. C., Lawler, J. E. (2000) ApJ **533**, L139.
8. Burris, D.L., Pilachowski, C.A., Armandroff, T., Sneden, C., Cowan, J.J., &Roe, H. (2000) ApJ, in press.
9. Cowan, J.J., Sneden, C., Truran, J. W., & Burris, D. L. (1996) ApJ, **460**, L115.
10. Sneden, C., Cowan, J.J., Burris, D.L., & Truran, J.W. (1998) ApJ **496**, 235.
11. Westin, J., Sneden, C., Gustafsson, B., & Cowan, J.J. (2000) ApJ **530**, 783.
12. Pagel, B.E.J. (1968) in *Origin and Distribution of the Elements*, ed. L.H. Ahrens (London, Pergamon Press), 195.
13. Truran, J.W. & Cameron, A.G.W. (1971) A&SS **14**, 179.
14. Mathews, G.J., Bazan, G., & Cowan, J.J. (1992) ApJ **391**, 719.
15. Ishimaru, Y. & Wanajo, S. (1999) ApJ **511**, L33.
16. Travaglio, C., Galli, D., Gallino, R., Busso, M., Ferrini, F., & Straniero, O. (1999) ApJ **521**, 691.
17. Fields, B., Truran, J.W., & Cowan, J.J. (2000), ApJ, submitted.
18. Ishimaru, Y. & Wanajo, S. (1999), ApJ, 511, L33.
19. Raiteri, C.M., Villata, M., Gallino, R., Busso, M., & Cravanzola, A. (1999) ApJ, 518, L91.

20. Argast, D., Samland, M., Gerhard, O.E. & Thielemann, F.-K. (2000) A&A, 356, 873.
21. Audouze, J. & Silk, J. (1995) ApJ, 451, L49.
22. Rosswog, S., Davies, M. B., Thielemann, F.-K. & Piran, T. (2000) A&A, 360, 171.
23. Wasserburg, G.J., Busso, M., & Gallino, R. (1996) ApJ **466**, L109.
24. Woosley, S.A., Wilson, J.R., Mathews, G.J., Hoffman, R.D., Meyer, B.S. (1994) ApJ **433**, 229.
25. Takahashi, K., Witti, J., Janka, H.-T. (1994) A&A **286**, 857.
26. Lattimer, J.M., Mackie, F., Ravenhall, D.G., Schramm, D.N. (1977) ApJ **213**, 225.
27. Freiburghaus, C., Rosswog, S., Thielemann, F.-K. (1999) ApJ **525**, L121-L124.
28. LeBlanc, J.M., Wilson, J.R. (1970) ApJ **161**, 541.
29. Truran, J.W., Cowan, J.J., & Cameron, A.G.W. (1978) ApJ **222**, L63-L67.
30. Thielemann, F.-K., Arnould, M., & Hillebrandt, W. (1979) A&A **74**, 175.
31. Blake, J.B., Woosley, S.E., Weaver, T.A., & Schramm, D.N. (1981) ApJ **248**, 315.
32. Cowan, J.J., Cameron, A.G.W., & Truran, J.W. (1985) ApJ **294**, 656.
33. Woosley, S.A. & Weaver, T.A. (1995) ApJS **101**, 181.