Neutron Capture Nucleosynthesis in Early Galactic Environments*

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Abstract. 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, the elements in the mass region past barium (A $\approx$ 140) have been found to be pure r-process products. The identification of an environment provided by massive stars and associated Type II supernovae as an r-process site seems compelling. 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. 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 are *primary* nucleosynthesis products, formed in an environment associated with the evolution of massive 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

* To appear in *The First Stars*

(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.

2 r-Process Nucleosynthesis at Early Galactic Epochs

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 bismuth in metal-poor stars. The heavy element abundance patterns for the two stars CS 22892-052 [4] and HD 115444 [5,6] are compared with the solar system r-process abundance distribution in Figure 1.

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 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.

A critical question here involves the abundances of r-process nuclei less massive than barium. The incompatibility of the abundances of the short lived radioactivities ^{107}Pd and ^{129}I in early solar system matter with a model of "uniform production" that works well, for both the actinide chronometers and the short lived isotope ^{182}Hf, led Wasserburg *et al.* [7] to argue for a second r-process component for the mass region below A $\approx$ 140. Studies of abundances in the mass range from the iron region through barium in low metallicity stars can be expected to provide significant input in this regard.

3 Constraints on r-Process Nucleosynthesis Sites

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

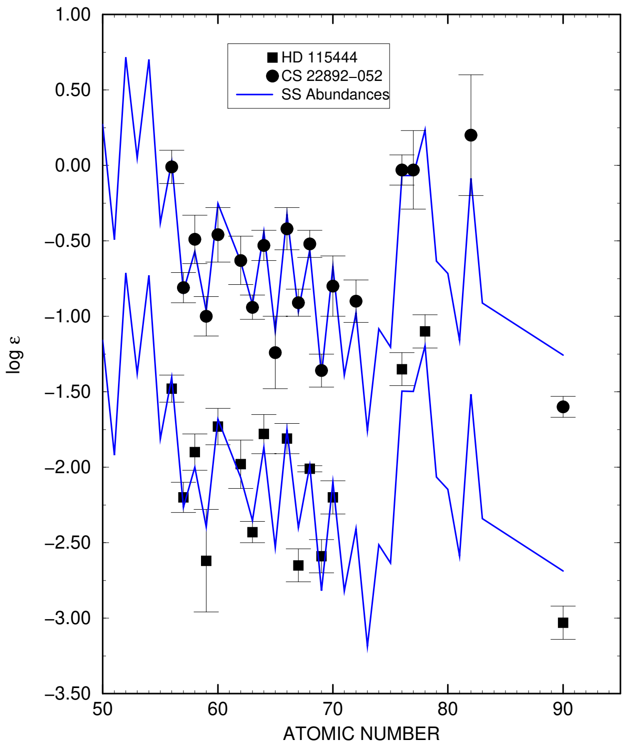

Fig. 1. The heavy element abundance patterns for the two stars CS 22892-052 and HD 115444 are compared with the scaled solar system r-process abundance distribution (solid lines) [4–6]

as a function of [Fe/H] for a large sample of halo and disk stars [8] in Figure 2. 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 [9]. 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.

4 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 ele-

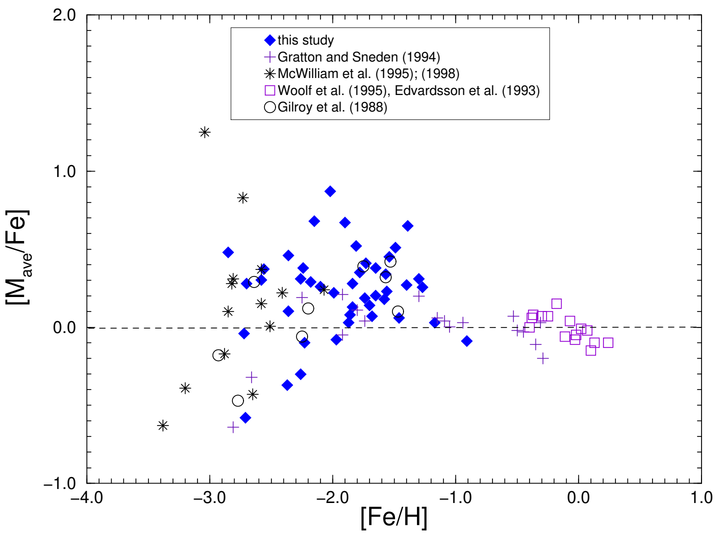

Fig. 2. The ratio [r-process/Fe] is displayed as a function of [Fe/H] for a large sample of halo and disk stars [8]

ment patterns as a function of [Fe/H] by Pagel [10] motivated theoretical consideration of such trends in the context of models of Galactic chemical evolution [11]. The great increase in abundance data for metal-poor stars over the past decade has similarly motivated considerable theoretical activity [12–14]. 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 [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.

5 Discussion and Conclusions

The observations reviewed in the previous sections provide great guidance to theoretical studies of r-process nucleosynthesis. They suggest: (1) the site of formation of the heavy r-process elements (A $>$ 130-140) must be associated with events that occur very early in the history of our Galaxy; (2) the r-process mechanism that operates in this environment must be robust, in the sense that even a single nucleosynthesis event seems capable of producing an r-process abundance distribution closely in agreement with that found in solar system matter; (3) this early r-process component can only operate in a relatively small fraction (of order 1/10th to 1/50th) of the massive stars that

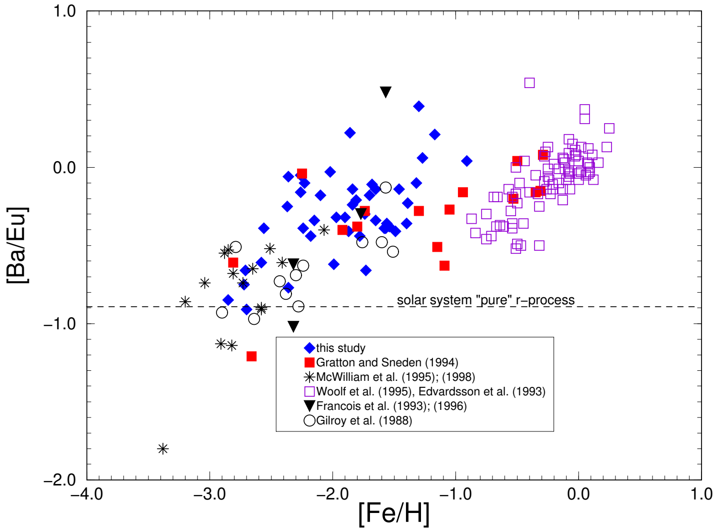

Fig. 3. The ratio [Ba/Eu], which reflects the ratio of s-process to r-process elemental abundances, is displayed as a function of [Fe/H] for a large sample of halo and disk stars [8]

produce iron; (4) a second r-process site/mechanism is required to account for both the levels of ^{107}Pd and and ^{129}I in primordial solar system matter and the r-process nuclei in the mass range 80 < A < 130-140 in solar matter; and (5) s-process contributions to barium and heavier nuclei are introduced into the ISM at later epochs than are r-process contributions.

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