The Early Formation, Evolution and Age of the Neutron-Capture Elements in the Early Galaxy[1]

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Abstract. Abundance observations indicate the presence of rapid-neutron capture (i.e., r-process) elements in old Galactic halo and globular cluster stars. These observations demonstrate that the earliest generations of stars in the Galaxy, responsible for neutron-capture synthesis and the progenitors of the halo stars, were rapidly evolving. Abundance comparisons among several halo stars show that the heaviest neutron-capture elements (including Ba and heavier) are consistent with a scaled solar system r-process abundance distribution, while the lighter such elements do not conform to the solar pattern. These comparisons suggest two r-process sites or at least two different sets of astrophysical conditions. The large star-to-star scatter observed in the neutron-capture/iron ratios at low metallicities – which disappears with increasing [Fe/H] – suggests an early, chemically unmixed and inhomogeneous Galaxy. The stellar abundances indicate a change from the r-process to the slow neutron capture (i.e., s-) process at higher metallicities in the Galaxy. The detection of thorium in halo and globular cluster stars offers a promising, independent age-dating technique that can put lower limits on the age of the Galaxy.

INTRODUCTION

In this paper we briefly review some of the important abundance trends for the slow- or rapid-neutron capture elements. We focus on how these neutron-capture elements can be employed to (1) study the nature of the progenitors and the nucleosynthesis history in the early Galaxy, (2) explore the chemical evolution of the Galaxy, and (3) obtain radioactive age estimates for the oldest stars, which in turn puts limits on the age of the Galaxy and the universe.

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[1]) To appear in the *Proceedings of the 20th Texas Symposium on Relativistic Astrophysics*, J. C. Wheeler & H. Martel (eds.)

NEUTRON-CAPTURE ABUNDANCES

Extensive abundance studies have been made of the ultra-metal-poor ($\equiv$ UMP, [Fe/H] = –3.1) but neutron-capture rich halo star CS 22892–052 [1–3]. In Figure 1 we show the n-capture abundances as determined by Sneden et al. [3] compared to a scaled solar system r-process abundance distribution. As has been noted previously, the upper end of the stellar abundance distribution (*i.e.*, Ba and above) is in very close agreement with the solar system r-process curve. It has been seen only recently, and so far only in this star, that the lighter n-capture abundances between Zr and Ba (*e.g.*, Nb, Pd, and Ag) do not lie on the same solar curve. This lends support to previous suggestions that there may be two sites for the r-process, one for the heavier and one for the lighter n-capture elements [4]. It is unclear whether both of those sites might be supernovae occurring at different frequencies [5] or neutron star binaries [6] or some combination of those. Alternatively, it has been proposed that both ends of the abundance distribution could be synthesized in different regions of the same neutron-rich jet of a core-collapse supernova [7].

ABUNDANCE TRENDS IN THE GALAXY

Observations of n-capture abundances in a wide range of Galactic, including metal-poor halo and disk, stars have now been made over a range of metallicities.

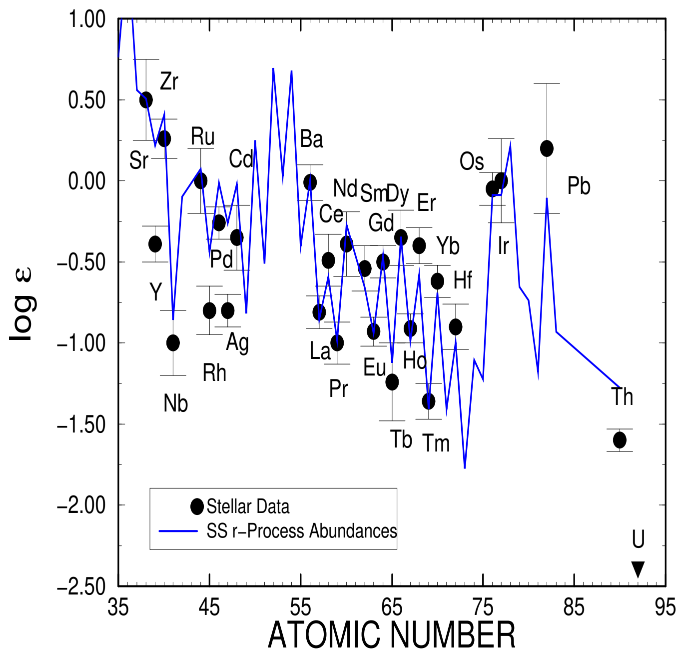

FIGURE 1. Neutron-capture abundances in CS 22892–052 compared with a scaled solar system r-process distribution (solid line).

These data demonstrate several interesting abundance trends in the Galaxy.

Scatter in the Early Galaxy

Earlier work by Gilroy *et al.* [8] first demonstrated that the stellar abundances of r-process elements with respect to iron, particularly Eu/Fe, showed a large scatter at low metallicities. This scatter appeared to diminish with increasing metallicity. A more extensive study by Burris *et al.* [9] confirmed the very large star-to-star scatter in the early Galaxy, while studies of stars with higher metallicities – mostly disk stars – [10,11] show little scatter. In Figure 2 we plot the data from a number of surveys [9–13], along with detailed abundance determinations from several single stars [3,14]. These studies, which cover a metallicity range $-3.5 \leq$[Fe/H]$\leq +0.5$ and include large numbers of stars, had attempted to minimize observational errors. The star-to-star scatter illustrated in this figure can be explained as the result of individual nucleosynthetic events (*e.g.*, supernovae) [8,9] and strongly suggests an early, unmixed, chemically inhomogeneous Galaxy. (See also [15] for further discussion.) It should be noted that while the absolute levels of n-capture/Fe abundances vary widely, the relative abundances are similar in all of the very metal-poor halo stars.

One other important trend is notable in Figure 2. At higher metallicities, particularly for [Fe/H] $\simeq -1$, the values of [Eu/Fe] tend downward. This demonstrates

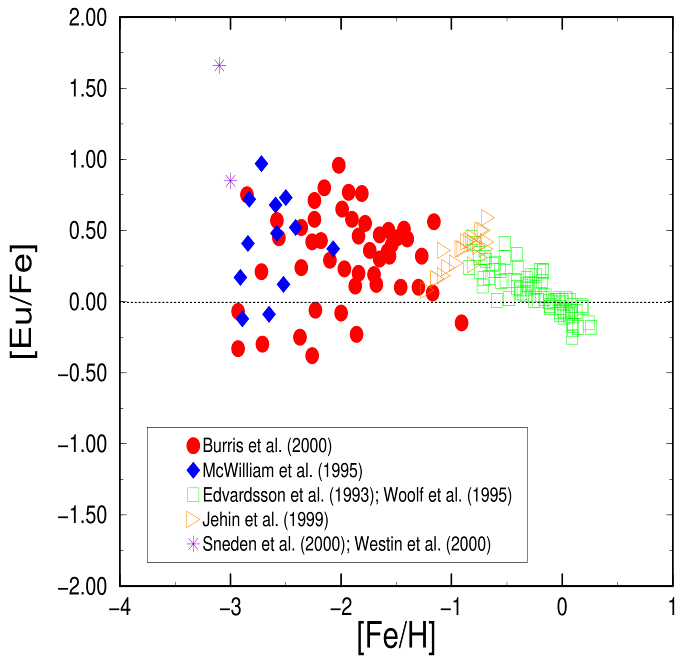

FIGURE 2. [Eu/Fe] vs. metallicity for Galactic halo and disk stars. The dotted line indicates the solar value.

clearly the effect of increasing iron production, presumably from Type Ia supernovae, at higher Galactic metallicities [9]. At very low metallicities high mass (and rapidly evolving) Type II supernovae contribute to Galactic iron production. The onset of the bulk of iron production from Type Ia supernovae (with longer evolutionary timescales due to lower mass progenitors) occurs only at higher [Fe/H] and later Galactic times.

Chemical Evolution of the *r*- and *s*-Process

The abundances observed for the elements in CS 22892–052 and other UMP halo stars demonstrate the early onset of the *r*-process in the Galaxy. These results (see Figure 1) also confirm earlier predictions [16] that elements synthesized by the *s*-process in the solar system (*e.g.*, Ba) were formed solely in the *r*-process early in the history of the Galaxy. Further confirmation of this early Galactic dominance of the *r*-process is seen in Figure 3, where we plot [Ba/Eu] as a function of [Fe/H]. We have utilized a combination of data sets [9–11,17–19], including some shown in Figure 2, to produce this new figure. It is clearly seen in Figure 3 that at the lowest metallicities the stellar Ba/Eu ratios cluster around the solar system (pure) *r*-process value. Eu is almost exclusively an *r*-process element, but Ba is produced predominantly in solar system material by the *s*-process in low mass (1-3 $M_\odot$) AGB stars [9]. At the lowest metallicities early in the history of the Galaxy, the halo stars show the products only of *r*-process nucleosynthesis from rapidly evolving (with

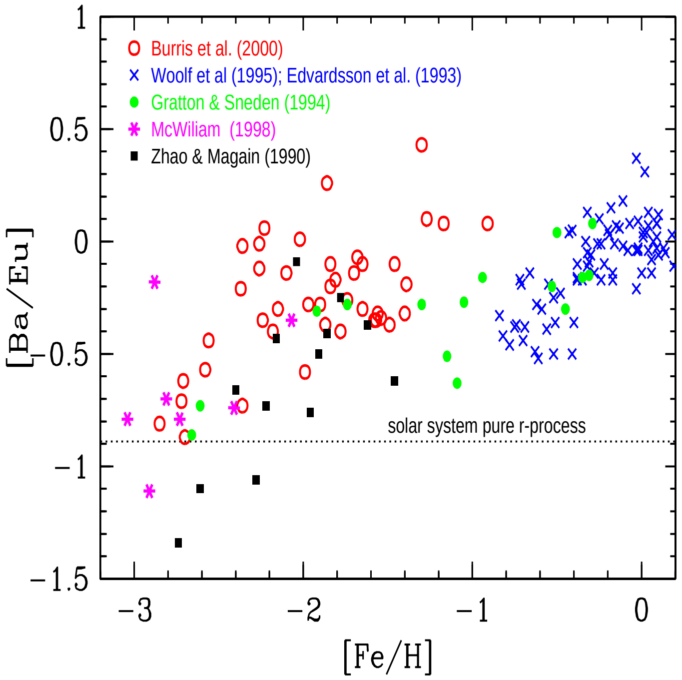

FIGURE 3. [Ba/Eu] vs. metallicity for Galactic halo and disk stars.

short stellar evolutionary timescale) progenitors typical of, for example, Type II supernovae. As the metallicity grows larger, the ratio of Ba/Eu rises due to the increased production of Ba (in the *s*-process) but not the *r*-process element Eu. The transition between a pure *r*-process production of Ba and production dominated by the main *s*-process occurs between $-3 < [Fe/H] < -2$, with most stars consistent with the (total) solar value of [Ba/Eu] for metallicities $[Fe/H] \geq -2$. The delay in the onset of the *s*-process with respect to the *r*-process is consistent with the longer stellar evolutionary timescales typical of low-mass (1–3 $M_{\odot}$) stars thought to be the site for *s*-process synthesis. It is interesting to note that the onset of the bulk of the main *s*-process in the Galaxy at $[Fe/H] \simeq -2$ occurs at a lower metallicity, and likely an earlier time, than the bulk of the iron production from Type Ia supernovae at $[Fe/H] \simeq -1$, as discussed above. We note further that while Ba has been commonly used for these abundance studies, in the future La may prove to be a more reliable indicator of the Galactic evolution of the *s*-process [15].

CHRONOMETRIC AGES

The detection of the radioactive element thorium in halo stars such as CS 22892–052 (see Figure 1) has provided the exciting opportunity of directly determining stellar ages. This technique relies upon comparing the observed stellar abundances with estimates of the initial abundance of the radioactive element. To minimize systematic errors, ratios of Th to Eu (produced almost exclusively in the *r*-process) are usually employed for these age determinations. Cowan *et al.* [20] and Westin *et al.* [14] obtained an average (minimum) age of 13.8 Gyr for the UMP stars CS 22892–052 and HD 115444 by comparing their observed Th/Eu abundances with the solar system ratio. This value represents a lower limit on their ages since Th has partially decayed over the last 4.5 Gyr. Improvements in these age estimates were then made by determining the initial (zero-decay) values of Th/Eu in the same calculations that reproduced the observed stable *n*-capture abundance distributions for both of these stars. The stable lead and bismuth solar system isotopic abundances were then employed to determine the most reliable mass formulae for predicting the properties of nuclei far from stability, critical for the theoretical *r*-process abundance calculations. Utilizing these constraints to obtain zero-decay Th/Eu abundances, an average age for CS 22892–052 and HD 115444 of 15.6 Gyr, with an estimated uncertainty of $\simeq$ 4 Gyr, was obtained [20,14].

In addition to studies of halo stars there have been recent observations of the globular cluster M 15 [21]. Detailed abundance determinations confirm that the heavier *n*-capture abundances are consistent with the scaled solar system *r*-process curve. Further, the detection of thorium in several of the globular stars has allowed a chronometric age estimate of 14 Gyr to be determined for this system [21].

Uranium, another long-lived radioactive element, can also serve as a chronometer. This element has not been detected to date in CS 22892–052 or in HD 115444, but has been found for the first time in the star CS 31082–001 [22]. Combining both chronometers Th and U, in conjunction with several stable heavy elements, an age of 12.5 $\pm$ 3 Gyr has been estimated for this star. While this technique still has some observational and theoretical uncertainties associated with it [23], it offers great promise. In particular such chronometric age estimates of UMP stars are independent of, and consequently avoid the large uncertainties in, Galactic chemical evolution models. Finally, we note that the radioactive age determinations of these oldest halo stars put meaningful constraints on both Galactic and cosmological age estimates.

ACKNOWLEDGMENTS

We thank all of our colleagues who have collaborated with us on various studies of n-capture elements in halo stars. This research has received support from NSF grants AST-9986974 to J.J.C., AST-9987162 to C.S. and from DOE contract B341495 to J.W.T., and from the Space Telescope Science Institute grant GO-8342.

REFERENCES

1. Cowan, J. J., *et al.*, *ApJ* **439**, L51 (1995).
2. Sneden, C., *et al.*, *ApJ* **467**, 819 (1996).
3. Sneden, C., *et al.*, *ApJ* **533**, L139 (2000).
4. Wasserburg, G. J., *et al.*, *ApJ* **466**, L109 (1996).
5. Wasserburg, G. J., and Qian, Y.-Z., *ApJ* **529**, L21 (2000).
6. Rosswog, S., *et al.*, *A&A* **341**, 499 (1999).
7. Cameron, A. G. W., *Nuclear Physics A*, in press (2001).
8. Gilroy, K. K., *et al.*, *ApJ* **327**, 298 (1988)
9. Burris, D. L., *et al.*, *ApJ* **544**, 302 (2000).
10. Edvardsson, B., *et al.*, *A&A* **275**, 101 (1993).
11. Woolf, V. M., *et al.* *ApJ* **453**, 660 (1995).
12. McWilliam, A., *et al.*, *AJ* **109**, 2757 (1995).
13. Jehin, E., *et al.*, *A&A* **341**, 241 (1999).
14. Westin, J., *et al.*, *ApJ* **530**, 783 (2000).
15. Sneden, C., *et al.*, in *Proceedings of Cosmic Evolution*, in press (2001) (astro-ph/0101439).
16. Truran, J. W., *A&A* **97**, 391 (1981).
17. Gratton, R., and Sneden, C., *A&A* **287**, 927 (1994).
18. McWilliam, A., *AJ* **115**, 1640 (1998).
19. Zhao, G. and Magain, P. *A&A* **238**, 242 (1990).
20. Cowan, J. J., *et al.*, *ApJ* **521**, 194 (1999).
21. Sneden, C., *et al.*, *ApJ* **536**, L85 (2000).
22. Cayrel, R., *et al.*, *Nature* **409**, 691.
23. Cowan, J. J., *et al.*, in *Proceedings of Cosmic Evolution*, in press (2001) (astro-ph/0101438).