Abundances and Ages in Halo Stars*

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Abstract. Ground-based and space-based observations have detected a large number of neutron-capture elements in metal-poor Galactic halo stars. The heavier n-capture elements (Z $\geq$ 56) in all of the most metal-poor stars observed to date have an abundance pattern consistent with the scaled solar system r-process abundance distribution. For the first time many lighter n-capture elements (from Z = 41–48) have been detected in the ultra-metal-poor star CS 22892–052. The abundances of these elements are not consistent with the solar system distribution and lend support to suggestions of more than one r-process site. Observations of r- and s-process elements indicate the early occurrence of the r-process at very low metallicities (i.e., early Galactic epochs) followed by the onset of the s-process at higher metallicities and later Galactic times. These observations also demonstrate a large star-to-star scatter in the n-capture/Fe abundance ratios at low metallicities. Utilizing the radioactive (r-process) element thorium, age determinations have been made for several of the metal-poor halo stars placing constraints on both Galactic and cosmological age estimates.

1 Introduction

The neutron-capture elements are formed as a result of either the rapid(r)- or the slow(s)-process. The abundances of these elements in metal-poor (i.e., low iron abundance) Galactic halo stars can be used to determine the nature of the progenitors and the nucleosynthesis history in the early Galaxy. In addition, abundance trends over changes in metallicities (and times) can provide clues about the nature of Galactic chemical evolution and the sites for n-capture synthesis. Finally, the abundances of long-lived radioactive elements (a.k.a. chronometers), such as thorium and uranium, in the metal-poor stars provides a direct stellar age determination.

2 Observations of Metal-Poor Halo Stars

Recent ground-based [1–4] and space-based [5,6] studies have been made to determine the abundances of the n-capture elements in metal-poor halo stars.

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Particular attention has been made of the ultra-metal poor, but n-capture rich, star CS 22892–052 [7,1,4]. Many elements detected in this star had not previously been seen in other such stars. Figure 1 illustrates a comparison of the n-capture abundances in CS 22892–052 with the scaled solar system r-process pattern. It is apparent from this figure that the heavier n-capture abundances (Z $\geq$ 56) are consistent with the solar system distribution.

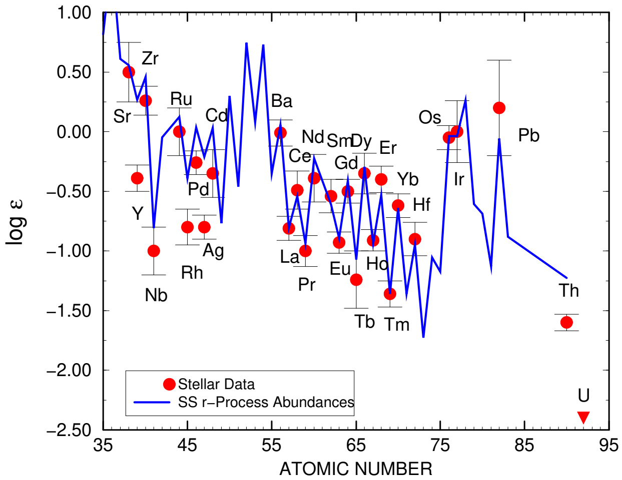

Fig. 1. The heavy element abundance patterns for CS 22892-052 compared with the scaled solar system r-process abundance distribution (solid line) [4]

While the abundance pattern for this star has been noted previously [7,1,8–10], there is new evidence that other stars show the same agreement with the solar r-process pattern. Recent work by Westin *et al.* (2000) obtained detailed abundance determinations for the metal-poor halo star HD 115444. Figure 2 illustrates a comparison of the abundance pattern of this star with CS 22892-052. (HD 115444 has been displaced vertically downward to make comparisons easier.) It is apparent that both stars have abundance patterns that mimic the solar system r-process distribution strongly suggesting that this behavior may be common in other halo stars. Additional support for this contention is found in the very recent work of Sneden et al. (2000b) who report that the abundances of the heavier (Z $\geq$ 56) elements for three stars in the globular cluster M15 are well matched by a scaled solar-system r-process abundance distribution.

Recently Sneden *et al.* (2000a) obtained detections of six new elements in the relatively unexplored elemental regime from Z = 41–48 in CS 22892–052. As is clear from Figure 1, the agreement between the heavier n-capture elements and the simple scaled solar system r-process pattern does not extend to the lighter elements below Ba. These observations lend support to suggestions [13] for a second r-process component for the mass region below A ≈ 140.

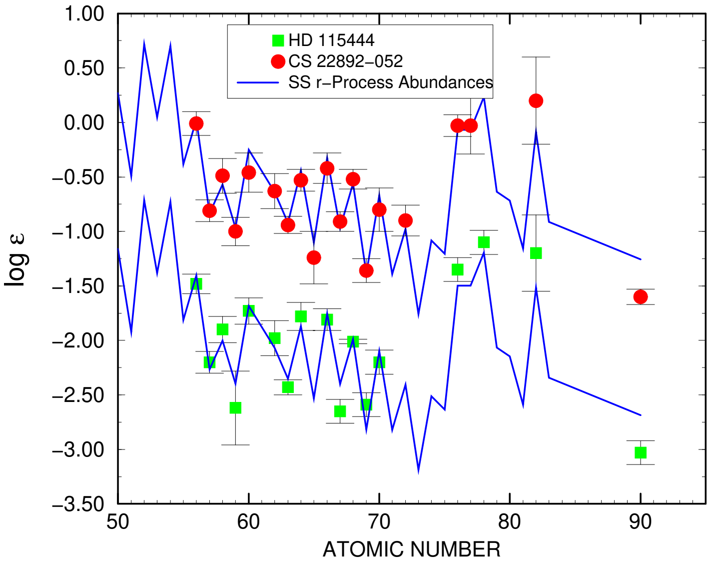

Fig. 2. The heavy element abundance patterns for the two stars CS 22892-052 and HD 115444 are compared with the scaled solar system r-process abundance distribution (solid lines) [1,11,4]

3 Galactic Abundance Trends

Since CS 22892 and HD 115444 are old (see below) and among the earliest generations of Galactic stars, the presence of the r-process elements in these stars demonstrates that the r-process operated early in the Galaxy, and points to rapidly evolving progenitors such as massive stars or perhaps neutron-star binaries [14]. Earlier suggestions [15], that even elements such as Ba, which are predominantly produced in the s-process, must have initially been synthesized in the r-process, are dramatically confirmed by the "pure" r-process pattern observed in stars such as CS 22892–052 and HD 115444. Additional insight into the nature and evolution of the n-capture elements is provided by stellar abundance studies for a range of metallicities. Burris et al. (2000) has recently detailed the changing nature of elemental synthesis with increasing metallicity. They also note the purely r-process nature of the abundances at lowest metallicities, with the onset of the s-process occurring near metallicities [Fe/H]=–2.7. Their study also confirms earlier work [16] demonstrating a pronounced scatter in the n-capture/iron abundance ratios in stars at lowest metallicities. This scatter, which is most likely due to an inhomogeneous, chemically unmixed Galaxy at early times, disappears at higher metallicities. Additional theoretical work to examine the nature of early Galactic nucleosynthesis is ongoing [17].

4 Chronometric Ages

As illustrated in Figure 2, thorium has been detected in both CS 22892–052 and HD 115444. Upper limits on the uranium abundance in both stars have also been obtained. [11,4]. Comparison of the observed stellar thorium abundance with the initial zero-age abundance produced in an r-process site leads directly to chronometric ages. Several studies [1,9–11,4] have determined ages for CS 22892–052 and HD 115444 on the order of 15 $\pm$ 4 Gyr. Sneden *et al.* (2000b) report on thorium detections in several stars in the globular cluster M15. They obtain ages that are consistent with those found for the halo stars. This technique offers promise as an independent dating technique which can provide (lower) limits on the age of the Galaxy, and hence, the universe.

5 Conclusions

Our ground-based and space-based observations, complemented by our theoretical studies, have (1) detected a number of neutron-capture elements, many for the first time, in halo (and globular stars). We have detected almost half (!) of the periodic chart in CS 22892–052. (2) The presence of neutron-capture elements from Ge through Th in these very old, metal-poor stars confirms the operation of an r-process in the early Galaxy. This further suggests rapidly evolving progenitors, either supernovae, or perhaps neutron-star binaries. (3) In the most metal-poor halo stars, and now in at least one globular cluster, where detailed observations are available, the heavy ($Z \geq 56$) n-capture elements have relative proportions consistent with the solar r-process abundances. In contrast, the lighter n-capture elements detected in CS 22892-052 do not follow the solar system pattern. This lends support to suggestions of more than one astrophysical r-process site. (4) The abundances of the n-capture elements, with respect to iron, demonstrate a large star-to-star scatter at the lowest metallicities. These Galactic abundance studies further show the onset of the s-process at a higher metallicity and presumably a later time. (5) Finally, the presence of Th in the metal-poor halo stars, as demonstrated in CS 22892–052 and HD 115444, and now at least some globular cluster stars, can be used to determine chronometric stellar ages and thus to put constraints on both Galactic and cosmological age estimates.

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References

1. Sneden, C., McWilliam, A., Preston, G.W., Cowan, J.J., Burris, D.L., Armosky, B.J. (1996) ApJ **467**, 819
2. McWilliam, A. (1998) AJ, **115**, 1640
3. Burris, D.L., Pilachowski, C.A., Armandroff, T., Sneden, C., Cowan, J.J., Roe, H. (2000) ApJ, in press
4. Sneden, C., Cowan, J.J., Ivans, I. I., Fuller, G. M., Burles, S., Beers, T. C., Lawler, J. E. (2000a) ApJ **533**, L139
5. Cowan, J.J., Sneden, C., Truran, J. W., & Burris, D. L. (1996) ApJ, **460**, L115
6. Sneden, C., Cowan, J.J., Burris, D.L., Truran, J.W. (1998) ApJ **496**, 235
7. Cowan, J. J., Burris, D. L., Sneden, C., Preston, G. W., McWilliam, A. (1995) ApJ, **439**, L51
8. Pfeiffer, B., Kratz, K.-L., Thielemann, F.-K. (1997) Z. Phys. A, **357**, 235
9. Cowan, J. J., McWilliam, A., Sneden, C., Burris, D. L. (1997) ApJ, **480**, 246
10. Cowan, J. J., Pfeiffer, B., Kratz, K.-L., Thielemann, F.-K., Sneden, C., Burles, S., Tytler, D., Beers, T. C. (1999) ApJ, **521**, 194
11. Westin, J., Sneden, C., Gustafsson, B., Cowan, J.J. (2000) ApJ, **530**, 783
12. Sneden, C., Smith, G. H., Johnson, J., Kraft, R. P., Cowan, J. J. Bolte, M. S. (2000b) ApJ, submitted
13. Wasserburg, G.J., Busso, M., Gallino, R. (1996) ApJ **466**, L109
14. Mathews, G.J., Bazan, G., Cowan, J.J. (1992) ApJ **391**, 719
15. Truran, J.W. (1981) A&A **97**, 391
16. Gilroy, K. K., Sneden, C., Pilachowski, C. A., Cowan, J. J. (1988) ApJ, **327**, 298
17. Truran, J.W., Fields, B.D., Cowan, J.J. (1999) preprint.