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EVIDENCE OF HEAVY ELEMENT NUCLEOSYNTHESIS EARLY IN THE HISTORY OF THE GALAXY: THE ULTRA-METAL-POOR STAR CS 22892–052

JOHN J. COWAN,[1] DEBRA L. BURRIS,[1] CHRISTOPHER SNEDEN,[2]
ANDREW MCWILLIAM,[3] AND GEORGE W. PRESTON[3]

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ABSTRACT

We analyze the neutron-capture element ($Z > 30$) abundance distribution of the ultra–metal-poor (but neutron-capture element rich) halo star CS 22892–052. The observed stellar elemental distribution is compared with those produced by the slow and rapid neutron capture processes (i.e., the *s*- and *r*-process) in solar system material. This comparison indicates that the elemental abundances, from barium to erbium, in this Galactic halo star, have the same relative proportions as the solar system *r*-process distribution. Within the uncertainties of the abundance determinations, the elements strontium and zirconium, but not yttrium, also fall on the same scaled solar *r*-process curve. The main component of the *s*-process cannot reproduce the observed neutron-capture abundances in this star. The weak component of the *s*-process, expected to occur during core helium burning in massive stars, can fit the relative abundance distribution of Sr and Y, but not Zr, suggesting that for the currently observed abundances in CS 22892–052, an admixture of the weak *s*- and the *r*-process might be required for production of the elements Sr to Zr. These results give evidence of the occurrence of heavy element nucleosynthesis, particularly the *r*-process, early in the history of the Galaxy, and further suggest a generation of massive stars (the astrophysical site for the *r*-process), preceding the formation of this very metal poor halo star, that was responsible for producing the observed heavy elements.

Subject headings: nuclear reactions, nucleosynthesis, abundances — stars: abundances — stars: individual (CS 22892–052) — stars: Population II

1. INTRODUCTION

The abundances of the metal-poor (and presumably old) halo stars can be used as a probe of the conditions that existed early in the history of the Galaxy. Specifically, the types and extent of nucleosynthetic processing that occurred in the stars that preceded the halo stars can be ascertained from these abundance determinations. There have been indications from previous observations that the rapid neutron-capture process (i.e., the *r*-process) was responsible for much of the synthesis of the heavy elements at early Galactic times (Spite & Spite 1978; Truran 1981). More recent observations have provided evidence that even many of the elements (e.g., Ba) normally thought to be produced in the slow neutron-capture process (i.e., the *s*-process) were also produced by the *r*-process at that time (Sneden & Parthasarathy 1983; Luck & Bond 1985; Sneden & Pilachowski 1985; Gilroy et al. 1988; Sneden et al. 1988; Gratton & Sneden 1994).

Although not certain, there is abundant evidence suggesting Type II supernovae, from massive stars, are the sites for the synthesis of the *r*-process nuclei (Cowan, Thielemann, & Truran 1991a, b; Meyer 1994). The *s*-process elements, on the other hand, are thought to be mostly formed during the late stages of evolution in lower mass stars with relatively long (i.e., gigayears) stellar lifetimes (Meyer 1994). Analysis of the heavy element abundance patterns can thus provide constraints on the mass range of stars that can produce such elements and on the timescale between the death of the progenitor stars and the formation of the halo stars.

In a previous *Letter*, Sneden et al. (1994, hereafter SPMS) reported on the ultra–metal-poor halo star CS 22892–052. With a metallicity of ([Fe/H] $\simeq -3.12$),[4] this is not the most metal poor star that has been discovered, but it is the lowest metallicity star for which we have extensive abundances of a number of very heavy elements ($Z > 30$). SPMS noted the strong overabundance of the neutron-capture elements in this star. In this *Letter*, we report on the results of an analysis of the abundance distribution of this very unusual star, which indicate the operation of the *r*-process and, perhaps, the weak component of the *s*-process from massive stars at a very low metallicity early in the history of the Galaxy.

2. OBSERVATIONS

For all elements except Dy, we adopted the abundances derived by SPMS. Brief descriptions of their data sets and reduction and analysis techniques may be found in that paper, and more elaborate discussions will appear in Preston et al. (1994) and McWilliam et al. (1994). Two observational points bear repeating here. First, the spectra, obtained with the Las Campanas echelle spectrograph, are reasonably high resolution ($R \simeq 22{,}000$) but only modest signal-to-noise (S/N $\simeq 35$). Thus some potentially interesting spectral features were lost in the spectrum noise. But partially mitigating this problem is the unique intrinsic spectrum of CS 22892–052: it is generally so metal-poor ([Fe/H] $\simeq -3.12$) but neutron-capture element

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[1] Department of Physics and Astronomy, University of Oklahoma, Norman, OK 73019.

[2] Department of Astronomy and McDonald Observatory, University of Texas, Austin, TX 78712.

[3] Carnegie Observatories, 813 Santa Barbara Street, Pasadena, CA 91106-1292.

[4] We adopt the usual spectroscopic notations in this *Letter*, namely $[X] \equiv \log_{10}(X)_{\rm star} - \log_{10}(X)_{\odot}$ for any abundance quantity X, and $\log \epsilon(X) \equiv \log(N_X/N_H) + 12.0$ for absolute number density abundances.

rich ($+0.3 \leq$ [n-capture/Fe] $\leq +1.8$) that many neutron-capture element features stand out in the spectrum in contrast to the overall line weakness of this star (see Fig. 1 of SPMS).

For the present work we have reconsidered only the Dy abundance. SPMS employed only two Dy II transitions (at 4073 and 4103 Å) in their study, and derived oscillator strengths for these features from an inverted solar analysis. Here, armed with new laboratory studies of Dy II by Grevesse, Noels, & Sauval (1993) and Biémont & Lowe (1993), we made a more intensive search for useful Dy II features on our Las Campanas spectra. Five features at (3996, 4050, 4073, 4103, and 4449 Å) proved useful for analysis. For these features, the comparison of oscillator strengths in the two lab studies, in the sense of Biémont & Lowe minus Grevesse et al., yielded good agreement: $\Delta \log gf = -0.05 \pm 0.02$ (scatter of single measurements $\sigma = 0.05$). Synthetic spectrum matches to the CS 22892–052 spectrum, using mean gf's from the lab studies, gave $\langle[\mathrm{Dy/Fe}]\rangle = +1.69 \pm 0.05$ ($\sigma = 0.11$). This new abundance is reasonably close to the value of +1.79 quoted by SPMS, but is to be preferred due to the larger number of features and the greater reliability of the oscillator strengths.

We also caution the reader that the SPMS abundances for Sr ($Z = 38$) and Er ($Z = 68$) probably are less reliable than those of other n-capture elements of CS 22892–052. The Er abundance is based solely on one partially blended line in a crowded spectral region. The Sr abundance comes only from the very strong Sr II resonance transitions at 4077 and 4215 Å (weakly confirmed by abundance upper limits from a higher excitation Sr II line at 4161 Å and a ground state line of Sr I at 4607 Å). The abundances derived from these resonance lines are fairly sensitive to choices of damping parameters and microturbulent velocities. Larger uncertainties should be attached to the Er and Sr abundances of CS 22892–052, pending further spectroscopic investigation.

3. RESULTS AND DISCUSSION

Observational constraints prevent isotopic spectroscopic determinations in metal-poor stars. Instead, elemental abundances are observed in these stars, and analyses of these observations require elemental comparisons. The most extensive isotopic component set available, of course, is the solar abundance distribution, which has been compiled by a number of investigators (see, e.g., Cameron 1982; Anders & Grevesse 1989). The difficulty in using these data has been in deconvolving the various nucleosynthetic contributions (i.e., from the r- and s-process) to the individual isotopic abundances. We have used the data of Käppeler, Beer, & Wisshak (1989), who measured a number of neutron capture cross sections and predicted solar abundances for the s-process nuclei, to make these elemental determinations. The abundance of the r-process nuclei, except in special cases for r-only nuclei, were then determined from the difference between the solar abundance and the s-process contribution to that isotope. Using Table 4 from Käppeler et al., we then summed over stable isotopes by element, separating the individual isotopic contributions, to determine an elemental solar system distribution for both the s-process and the r-process. We then compared the observations from SPMS, along with the new Dy determinations discussed above, with these theoretical elemental distributions for the solar system s- and r-processes. Since CS 22892–052 is very metal poor with respect to the Sun, we shifted the solar system curves vertically downward (by a single scale factor) to compensate for the lower metallicity. The results of our comparison are shown in Figure 1a, which plots the abundance, in the usual spectroscopic units of $\log \epsilon$, versus atomic number, Z. While total solar abundance levels are of course higher by a factor of ~ 100 in the Sun, the relative proportions of the elements Ba-Er in CS 22892–052 are strikingly similar to the r-process elemental distribution in the solar system. For Figure 1a, both the r- and s-process curves were arbitrarily fitted at the element Nd (using the results from SPMS), as previous work (see Gilroy et al. 1988) indicated less observational scatter for that element in the metal-poor halo stars. Clearly, the choice of normalization does not matter for the r-process curve. For the s-process, however, the distribution could be moved vertically to try and improve the fit, but inspection of Figure 1a shows that the s-process can match very few of the observed heavy elements. (See also Fig. 1b, which compares the residuals between the observed and theoretical abundances.)

While Sr, Y, and Zr were observed in CS 22892–052, there are no observed elements between Ba and Zr. Nevertheless, we extended the r- and s-process abundance curves (used to fit Ba-Er) down to the much lower mass numbers typical of Sr-Zr, employing the same scaling and normalization as before. It is

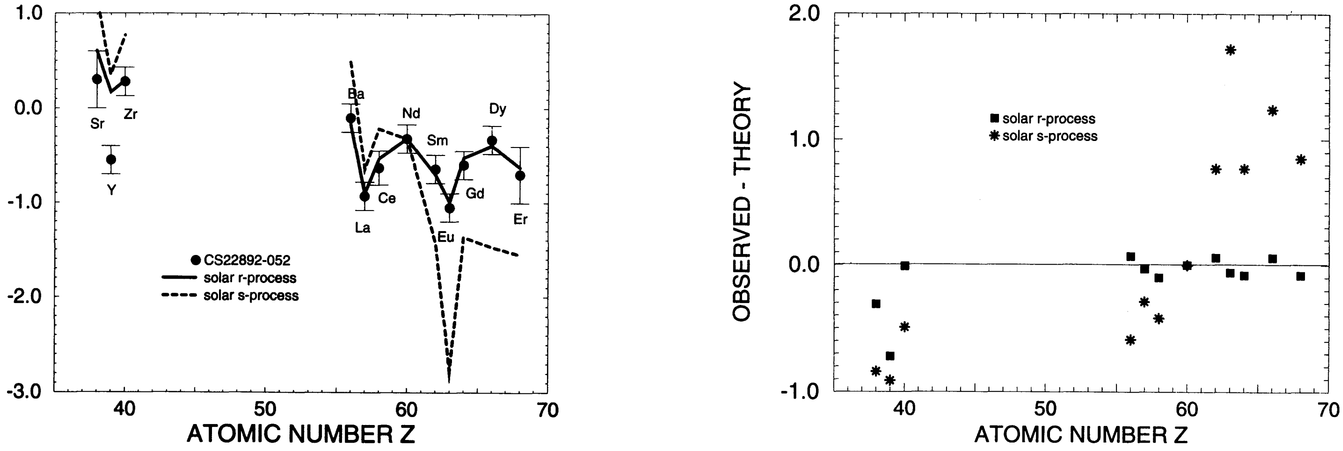

FIG. 1a

FIG. 1b

FIG. 1.—(a) CS 22892–052 elemental abundances from SPMS compared with the theoretical determinations of the solar r- and s-process elemental distribution. (b) Comparison of observed minus theory, as a function of atomic number, for the solar r- and s-process.

interesting to note that the observed abundance of Zr falls right on the solar system *r*-process curve, and, within the error bars, so does Sr. Unfortunately, this same distribution is not able to reproduce the abundance of Y, as illustrated in Figures 1*a* and 1*b*.

Although the heavier nuclei in the main component of the *s*-process are likely produced in low- and intermediate-mass red giants during the late stages of stellar evolution, the *s*-process isotopes up to mass A $\simeq 90$ are thought to be synthesized in the cores of massive stars ($M \geq 10\ M_{\odot}$) near the end of the helium burning phase (Lamb et al. 1977; Prantzos, Hashimoto, & Nomoto 1990). These so-called weak *s*-process nuclei include those forming the elements Sr-Zr. The models of Raiteri et al. (1993), for the synthesis of the weak *s*-process nuclei in massive stars, were used to obtain an elemental curve for this component of the *s*-process. In an attempt to match the observations of Sr-Zr, we arbitrarily fitted this curve to the abundance of Y, as illustrated in Figure 2*a*. It is seen that the relative proportions of the abundances of Sr and Y can, in fact, be matched in this weak-*s* model. Zr with mass numbers from 90 to 96, however, cannot be reproduced in this model for the weak *s*-process. (We found a similar result using the solar weak *s*-process abundances of Käppeler et al. 1989, with an even lower production of Zr isotopes.) Thus, assuming the operation of the weak *s*-process for these three elements, an additional contribution of $\sim 50\%$ of the solar *r*-process is needed to produce the Zr abundance. This arbitrary admixture of the weak *s*- and *r*-process, along with the solar *r*-process for the elements Ba-Er can then replicate the total abundances observed in CS 22892−052, as shown in Figure 2*b*. Alternatively, the current observations would be consistent with a weak *s*-process origin for Sr and Y, and a solar *r*-process distribution for all other elements in CS 22892−052. This would imply, however, a very sharp (and seemingly unphysical) cutoff/cuton of the weak *s*-process/*r*-process near mass number 90.

Whatever the eventual resolution of the Sr-Y-Zr question, all evidence points to massive star progenitors of this metal-poor halo star. Most of the elements (in fact, all except Y) observed in this star can be explained as coming from the *r*-process, most likely synthesized in supernova explosions of massive stars. The lack of significant contribution from the main component of the *s*-process very early in the history of the Galaxy is also consistent with suspected sites of the *s*-process being low- or intermediate-mass stars. The timescale for the stellar evolution of these low- and intermediate-mass stars appears to be longer than the formation time of the metal-poor halo stars. Assuming an *r*-process origin for the most heavy elements, along with an admixture of the weak *s*-process (synthesized only in massive stars) and the *r*-process for the elements Sr-Zr, also suggests massive star progenitors of the halo stars.

Our results also support the argument that for the metal poor halo stars, the heavy elements, specifically Ba-Er, are produced in the *r*-process in solar proportions. While this has been suggested before (Gilroy et al. 1988), it has never before been demonstrated for such a low metallicity.

Although the astrophysical site for the synthesis of the *r*-process nuclei is presumably Type II supernova explosions (Cowan et al. 1991a; Meyer 1994), it is not clear whether higher mass (i.e., $\sim 25\ M_{\odot}$) or lower mass (i.e., $\sim 10\ M_{\odot}$) supernova progenitors could have been responsible (see Mathews & Cowan 1990; Mathews, Bazan, & Cowan 1992). (We also note that neutron star binaries are thought to be a possible site for the *r*-process [Mathews et al. 1992].) Our current results cannot distinguish between these mass ranges as the site for the *r*-process, nor can we rule out the possibility that there were several generations of progenitors preceding the formation of CS 22892−052. We note, however, that the heavy element to iron ratio for this star is larger than other observed, and more metal rich stars (SPMS). While at higher metallicities ($[\mathrm{Fe/H}] > -2$) the Galaxy appears to be well mixed (Wheeler, Sneden, & Truran 1989), the heavy element to iron ratio for this metal-poor halo star strongly implies the timescale for chemical mixing in the early Galactic halo was longer than the timescale for the formation of CS 22892−052. Further, the large overabundances of the heavy, neutron-rich elements are most likely explained as resulting from a single, local nucleosynthetic effect, i.e., a supernova explosion near the formation site of CS 22892−052.

Extrapolating our results for the elements Ba-Er, we would expect that the very heavy elements, such as lead and bismuth,

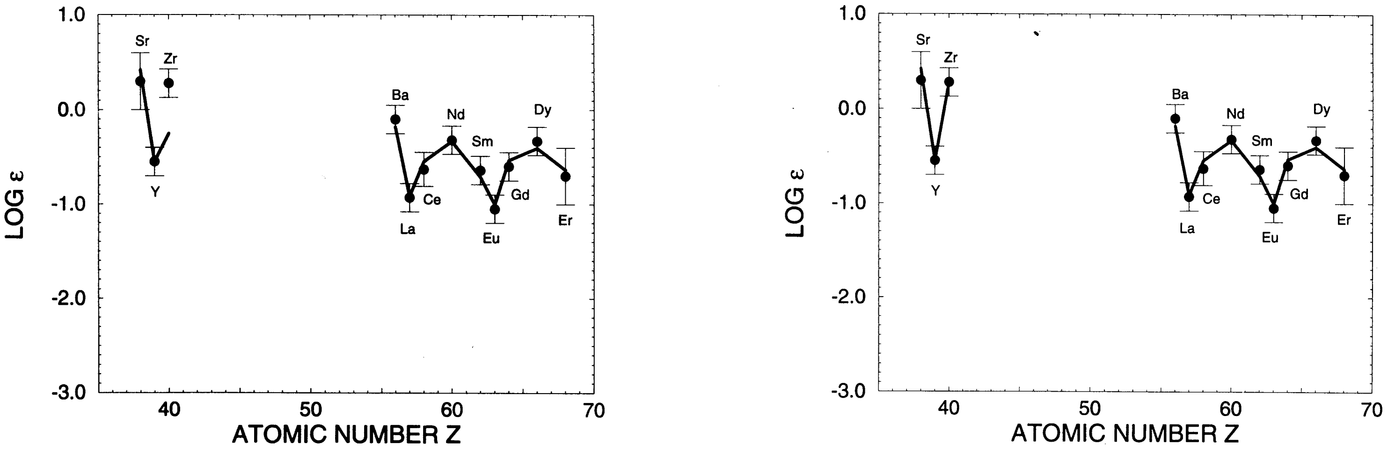

FIG. 2*a*

FIG. 2*b*

FIG. 2.—(*a*) Theoretical fit to the abundances in CS 22892−052 assuming a relative solar *r*-process distribution for the elements Ba-Er, and the predicted abundances of Sr, Y, and Zr from the weak *s*-process models of Raiteri et al. (1993). (*b*) Same as (*a*) except an additional contribution from the *r*-process is assumed for Zr.

should be observable in this star at abundance levels comparable to the heavy elements already observed. If so, that would further suggest the possibility of determining the thorium abundance, important for determining nucleosynthetic chronometer ratios (e.g., Th/Eu), and hence the age of this star and the Galaxy. Our current results for CS 22892−052 also demonstrate the need for additional heavy element observations of even more metal poor stars. Such observations will be necessary to constrain the mass of the presumably massive Population II progenitors and to provide more insight into the onset of nucleosynthesis and the early evolution of the Galactic halo.

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