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AN EXTREMELY METAL-POOR STAR WITH *r*-PROCESS OVERABUNDANCES

CHRISTOPHER SNEDEN[1]
Department of Astronomy and McDonald Observatory, University of Texas at Austin
AND
CATHERINE A. PILACHOWSKI
Kitt Peak National Observatory, National Optical Astronomy Observatories
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ABSTRACT

A high-resolution spectroscopic study of the very metal-deficient giant HD 110184 confirms the presence of strong rare earth features. An abundance analysis relative to the classic metal-poor giant HD 122563 yields heavy element abundance enhancements of roughly a factor of 2 for iron-peak elements, but factors of 4–10 for the heavy elements. The heavy element abundance pattern in HD 110184 is consistent only with *r*-process neutron synthesis reactions in preceding stellar generation(s). The great difference seen in the total heavy element content of these two halo stars is evidence for the influence of local supernovae in the chemical compositions of very metal-deficient stars.

Subject headings: nucleosynthesis — stars: abundances — stars: evolution

I. INTRODUCTION

In a recent detailed abundance study of the classical metal-poor giant HD 122563, Sneden and Parthasarathy (1983, hereafter SP) demonstrated that the heavy element abundance pattern in that star could be used to define nucleosynthesis sites in the early Galaxy. Briefly, they argued that the relative abundances of rare earth elements from Ba through Yb in HD 122563 signaled the existence of active *r*-process neutron synthesis reactions in the preceding stellar generations. The *s*-process did not make a large contribution to the rare earth element abundances and apparently only played a role in the formation of the lighter elements Sr, Y, and Zr. SP suggested that the total abundance pattern in HD 122563 was consistent with element synthesis in massive star supernova explosions early in our Galaxy's history.

That paper also noted the apparent existence of a very large scatter (about ±0.8 dex) in the Eu to Fe ratio in very metal-poor stars (see Fig. 1 of SP). In particular, while several studies agree that HD 122563 has a subsolar Eu/Fe value, some weaker observational evidence exists for significantly supersolar Eu/Fe ratios in other stars. As part of a large program to provide a detailed description of the heavy element abundances in very metal-poor stars, we have observed the halo giant HD 110184, which has been claimed to possess large amounts of europium: [Eu/Fe] ~ +0.8[2] (Luck and Bond 1981). In this *Letter* we will show that the Luck and Bond (1981) result is indeed qualitatively correct, and that *all* very heavy elements are much more abundant in HD 110184 than in HD 122563.

II. OBSERVATIONS AND REDUCTIONS

High-resolution, high signal-to-noise ratio spectra of HD 110184 were obtained with the Kitt Peak National Observatory 4 m telescope, Cassegrain echelle spectrograph, and an RCA 320 × 512 CCD detector with extended blue response. We also obtained identical spectra of HD 122563 for use as a comparison star. Approximately nine echelle orders appeared on each of three CCD images, and the central order wavelengths were near 4200 Å, 4450 Å, and 6200 Å. The CCD chip was large enough to provide nearly full spectral coverage for the blue orders, but the increase in echelle-free spectral range with wavelength prevented capturing the complete orders in the red. The spectral resolutions were approximately 0.17 Å, again varying with wavelength. The signal-to-noise ratio values of the spectra varied from about 40 at 4100 Å to about 100 at 6500 Å, due both to the increase in CCD quantum efficiency toward the red, and to the redward increase in flux from these K giants.

We extracted the spectra from the CCD images using standard software developed at KPNO for bias subtraction, flat-field correction, and cosmic-ray suppression. Final reduction of the spectra, involving conversions to wavelength scales, Fourier transform smoothing, and equivalent width measurements, were performed at Texas, using the spectrum software package written by Uumoto (1981). A comparison of equivalent widths of HD 122563 measured from our spectra with those published by SP showed excellent agreement: the average difference for single-line measures was ±4 mÅ, irrespective of line equivalent width.

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[1] Visiting Astronomer, Kitt Peak National Observatory, National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc. under contract with the National Science Foundation.

[2] We adopt the usual definition that $[X] \equiv \log_{10}(X)_{\rm star} - \log_{10}(X)_{\rm std}$, where std is the standard comparison star.

III. MODEL ATMOSPHERE PARAMETERS AND ABUNDANCES

HD 110184 is an extremely metal-poor K giant, quite similar to the well-studied HD 122563. Therefore we chose to derive model atmosphere parameters for this star relative to HD 122563. The paper of SP contains an extensive discussion of the determination of atmosphere parameters for HD 122563 from both an absolute and a differential analysis. Here we chose simply to take a rough mean of the values from both analyses for that star, adopting ($T_{\rm eff}$/log g/[Fe/H]/$v_{\rm micro}$) = (4600 K/1.20/− 2.6/2.3 km s^{-1}). These parameters are very consistent with those derived by other investigations of HD 122563.

We performed a differential fine analysis of the iron-peak lines in HD 110184 relative to those in HD 122563, employing interpolated model atmospheres from the grid of Bell *et al.* (1976) and the LTE line analysis codes of Sneden (1973). With the standard criteria that abundances from individual lines of an element show no trends with excitation potential, equivalent width, wavelength, and ionization state, we derived a model atmosphere parameter set of (4500 ± 150 K/0.85 ± 0.4/− 2.3 ± 0.25/3.0 ± 0.4 km s^{-1}) for HD 110184. The parameter uncertainties were determined by noting the effects on the abundances due to systematic variations in the trial model atmospheres. Luck and Bond (1981) also determined a model atmosphere for HD 110184 with line data from photographic coudé spectrograms. The parameters from their analysis, (4425 ± 200 K/1.00 ± 0.3/− 2.32 ± 0.15/3.8 ± 0.5 km s^{-1}), agree quite well with our results, even though they used the Sun, not HD 122563, as their standard star.

We derived abundances for all elements lighter than Sr differentially with respect to HD 122563. In Table 1 we list those abundances in HD 110184, in HD 122563, and also those in the Sun; a more extensive discussion of the abundances in HD 122563 and the Sun is given in SP. Our abundances for HD 110184 agree well with those of Luck and Bond (1981) for those species with more than a few lines measured in each study. For the heavier elements we employed an absolute analysis to derive abundances, adopting the oscillator strengths recommended by SP. An inspection of the spectra of the two stars suggested immediately that the heavy element line strengths were much larger in HD 110184 than could be due to the cooler temperature and 0.3 dex higher overall metal abundance of HD 110184. In Figure 1 we show an example of the differences seen between these spectra. The increased strengths of heavy element lines in HD 110184 permitted the use of different (and sometimes more) features in the present analysis than were possible in the work of SP on HD 122563. Moreover, the heavy element lines were strong enough to allow single-line analysis; synthetic spectrum techniques proved unnecessary here. Final abundances of these elements are given in Table 1 also. Heavy element overabundances also appear when determined from a differential analysis and thus are not dependent upon our particular choices of oscillator strengths. Note that the relative abundances among the heavy elements are fairly insensitive both to model atmosphere parameter uncertainties (see the discussion of errors in SP) and to possible departures from LTE in the stellar atmospheres (since this is a differential analysis between two very similar stars).

TABLE 1

ABUNDANCES IN HD 110184

	SUN	HD 122563[a]		HD 110184[a]			
SPECIES	log ε[b]	log ε	[M/H]	log ε	[M/H][c]	[M/H][d]	Lines
Mg I	7.62	5.25	−2.35	5.75	−1.85	0.50	2
Ca I	6.34	4.15	−2.20	4.45	−1.90	0.30	8
Sc II	3.08	0.50	−2.60	0.80	−2.30	0.30	3
Ti I	4.98	2.60	−2.40	2.80	−2.20	0.20	7
Ti II	4.98	2.60	−2.40	2.90	−2.10	0.30	13
V I	4.14	1.50	−2.65	1.60	−2.55	0.10	3
Cr I	5.7:	2.9:	−2.8:	3.2:	−2.5:	0.3:	2
Cr II	5.7:	3.1:	−2.6:	3.4:	−2.3:	0.3:	1
Fe I	7.58	5.10	−2.50	5.40	−2.20	0.30	89
Fe II	7.58	5.00	−2.60	5.20	−2.40	0.20	10
Ni I	6.29	3.70	−2.60	4.05	−2.35	0.35	4
Sr II	2.90	0.15	−2.75	1.10	−1.80	0.95	2
Y II	2.24	−0.70	−2.95	−0.15	−2.40	0.55	1
Zr II	2.56	0.15	−2.70	0.55	−2.00	0.40	2
Ba II	2.09	−1.40	−3.50	−0.75	−2.85	0.65	3
La II	1.13	−2.20	−3.35	−1.10	−2.25	1.00	3
Ce II	1.55	< −1.40	< −2.95	−0.95	−2.50	> 0.45	5
Pr II	0.99	−2.3:	−3.3:	−1.8:	−2.8:	0.5:	3
Nd II	1.26	−1.9:	−3.2:	−0.90	−2.15	1.0:	3
Sm II	0.80	< −2.35	< −3.15	−1.35	−2.15	> 1.00	4
Eu II	0.51	−2.40	−2.90	−1.35	−1.85	1.05	2
Gd II	1.12	−2.00	−3.10	−1.10	−2.20	0.90	2
Dy II	1.06	−1.90	−2.95	−1.05	−2.10	0.85	2

[a] All abundances for HD 122563 and HD 110184 have been rounded to the nearest 0.05 dex.

[b] All values of log ε have been normalized to log ε(H) ≡ 12.

[c] Relative to the Sun.

[d] Relative to HD 122563.

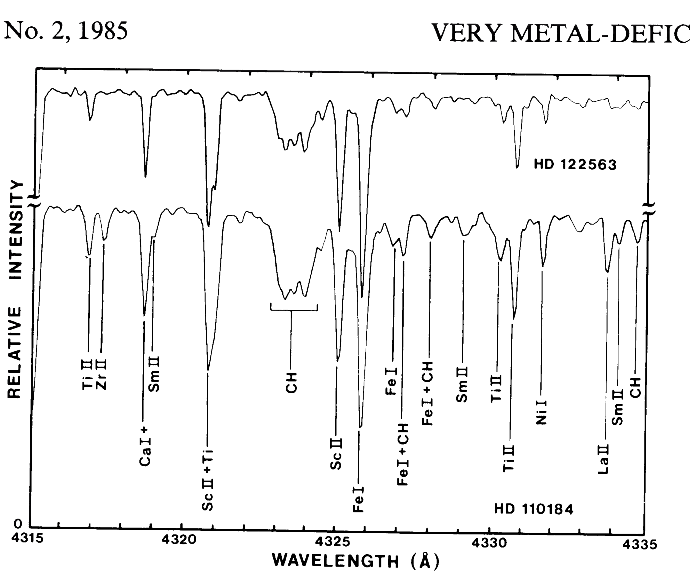

FIG. 1.—A small region of spectrum in HD 110184 and in HD 122563. While HD 110184 exhibits generally stronger absorption features, its very heavy element lines show larger enhancements than do its iron-peak lines.

IV. DISCUSSION

The heavy element abundances in HD 110184 contain two features important for galactic nucleosynthesis theory: (1) a nearly perfect match of the heavy element abundance distribution to expected yields from *r*-process synthesis events; and (2) total heavy element abundances much higher than those of HD 122563. In Figure 2 we have plotted the abundances of the heavy elements in HD 110184, along with "theoretical" abundance distributions resulting from *s*- and *r*-process synthesis events. For illustration of the *s*-process we have shown a theoretical exponential distribution model with $\tau = 0.10$, taken from the paper of Cowley and Downs (1980), and normalized to the observed Ba abundance. We chose to plot an *s*-process abundance curve which most closely fit the observed ratio of Sr-Y-Zr to Ba, for these elements represent the most easily observed parts of the two major *s*-process peaks. The data of Figure 2 show clearly that this model does not work. Furthermore, *no* other *s*-process model comes close to simultaneously producing the proper amounts of the elements Sr through Nd. For instance, if we would choose a model with a larger exposure parameter τ in order to generate comparable abundances of Ba, Ce, and Nd, *all* of these elements would be overproduced with respect to Sr, Y, and Zr. Also, no *s*-process model will produce the observed Ba/Eu ratio, which is not surprising since large amounts of Eu can be made only in the *r*-process. More importantly here, all *s*-process models fail to make the observed amount of La. In HD 110184 we observe $\log\{\varepsilon(\mathrm{Ba})/\varepsilon(\mathrm{La})\} \approx +0.35$, while theoretical *s*-process distributions exhibit $\log\{\varepsilon(\mathrm{Ba})/\varepsilon(\mathrm{La})\} \approx +1.0$, varying little with τ. The Ba/Eu and Ba/La ratios also rule out a simple combination of two *s*-process episodes with different neutron exposures.

No detailed abundance predictions exist for the *r*-process, so following the procedure of SP, we have plotted in Figure 2 an *r*-process distribution by adopting Cameron's (1982) assessment of the *r*-process fraction of the solar system abundances of the elements, and then normalizing this distribution to the abundance of Eu in HD 110184. Other theoretical *r*-process abundance curves could be quite different in detail than the one displayed here. The scaled solar curve matches well the abundances of *all* elements beginning with Ba, except for the uncertain Pr abundance. In particular, an *r*-process abundance curve predicts well the observed ratios Ba/Eu and Ba/La. This point was made in SP's work on HD 122563 (following the suggestion by Truran 1981), but the extreme weakness of heavy element lines in that star's spectrum resulted in upper limits or very uncertain abundances for some elements. Also, the Ba abundance in HD 122563 could not be explained purely by *r*-process synthesis; some *s*-process contribution was necessary to match its observed abundance. The heavy element abundance pattern in HD 110184 presents a much stronger case for the dominance of the *r*-process formation of heavy elements in metal-poor stars.

An *r*-process abundance distribution somewhat underproduces Sr and Zr, so we have added a final curve to Figure 2 showing the addition of the *r*-process distribution and a very short exposure theoretical distribution, with $\tau = 0.08$, from Cowley and Downs (1980). Obviously this improves the fit for the Sr-Y-Zr peak, while having little effect on the abundances of heavier elements. This is consistent with a short episode of *s*-processing during core helium burning of the presupernova progenitor to HD 110184. Even with this small addition of some *s*-processing, the Y/Eu and Ba/Eu ratios remain less

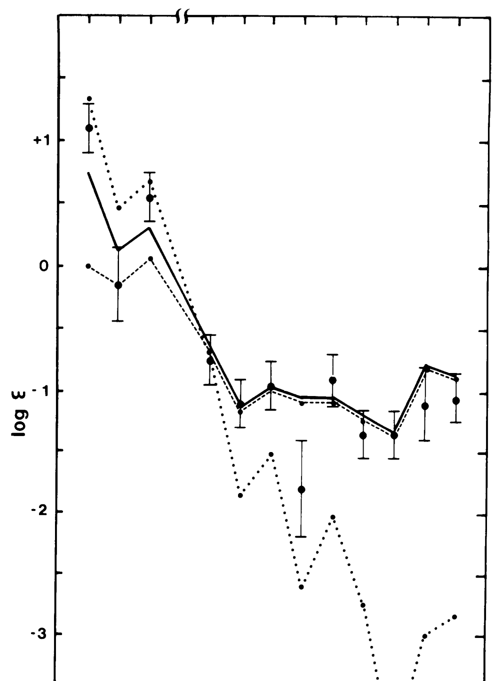

FIG. 2.—The heavy element abundances of HD 110184 and abundance distribution curves of the *s*- and *r*-process. The filled circles are the observed abundances. The dotted line represents a theoretical *s*-process abundance distribution, the dashed line is for a scaled solar system *r*-process distribution, and the solid line represents the same *r*-process curve with a small addition of some *s*-processing to increase the abundances of Sr and Zr.

than the solar system values, which Truran (1981) argues is characteristic of a dominant *r*-process.

Finally, simple averages of the abundances of the elements Ca through Ni, and Ba through Dy clearly suggest that for HD 110184, $[\text{Fe-peak/H}]_{122563} \approx +0.25$, while $[\text{heavy element/H}]_{122563} \approx +0.85$. SP noted that all heavy elements, even those normally attributed to the *r*-process, were deficient in HD 122563 and discussed ways in which the Fe-peak elements could build up in the Galaxy before the *r*-process elements (e.g., through assignment of *r*-process synthesis to helium flashes in low-mass stars; Cowan, Cameron, and Truran 1982). The chemical composition of HD 110184 suggests that such schemes may be unnecessary. Of the heavy elements, only Ba, and perhaps Pr, appear underabundant with respect to Fe relative to the solar composition. Also, Eu exhibits a significant *over*abundance: $[\text{Eu/Fe}]_{\text{Sun}} \approx +0.45$. A genuine scatter of [*r*-process/Fe] in metal deficient stars seems indicated by this result.

The heavy element abundances of extremely metal-poor stars may be exhibiting the results of single nucleosynthesis events in the young and not completely mixed Galaxy. The recent discovery of the Population II "barium star" HD 115444 by Griffin *et al.* (1982) provides additional evidence of significant star-to-star variations in the heavy element contents of very metal-poor stars. The heavy element abundances in that star are similar to those of HD 110184, but the Ba abundance in HD 115444 apparently does require a significant contribution by the *s*-process. Further investigation of this unusual star is desirable.

The observations for this program were made during a highly successful remote observing run with the KPNO 4 m telescope. We thank the engineers and technical staffs of both KPNO and McDonald Observatory for getting the remote system to work very efficiently. We are grateful to D. Lambert and J. Cowan for helpful discussions. This work has been supported by NSF grant AST-8219340 to C. S.

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CATHERINE A. PILACHOWSKI: Kitt Peak National Observatory, National Optical Astronomy Observatories, Box 26732, Tucson, AZ 85726-6732

CHRISTOPHER SNEDEN: Department of Astronomy and McDonald Observatory, University of Texas, Austin, TX 78712