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ULTRAMETAL-POOR HALO STARS: THE REMARKABLE SPECTRUM OF CS 22892−052

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ABSTRACT

The star CS 22892−052, discovered in the HK Objective-Prism survey of the southern Galactic halo, is extremely weak-lined at low resolution. At higher resolution, features of very heavy neutron-capture elements and CH dominate the spectrum. An abundance analysis reveals that this star is indeed very metal-poor: [Fe-peak/H] ~ -3.1. The α elements Mg, Ca, and Ti are enhanced by factors typical for halo stars, $[\alpha/\mathrm{Fe}] \simeq +0.4$. The neutron-capture elements are strongly overabundant: $+0.3 <$ [*n*-capture/Fe] $< +1.8$ in the range $38 \leq Z \leq 68$, with the enhancements generally growing with increasing Z. The ratio [C/Fe] $\sim +1$ also is much larger than in any other known star of this metallicity range. The total *n*-capture element distribution is well represented by an *r*-process nucleosynthesis yield. This star provides the clearest evidence for element enrichment from "local" supernovae nucleosynthesis events in an unmixed early Galactic halo.

Subject headings: Galaxy: halo — Nuclear reactions, nucleosynthesis, abundances — stars: abundances — stars: individual (CS 22892−052) — stars: Population II

1. INTRODUCTION

The chemical compositions of extremely metal-poor stars offer direct and detailed evidence of early Galactic nucleosynthesis. A long-sought goal of this work is the discovery of stars whose heavy element abundances reflect the output of the "first generation" of Galactic supernovae. Of even greater interest would be the identification of a star whose abundance ratios reveal the seeding of its prestellar ISM cloud by a single supernova. At the present time however, halo stars in the metallicity[4] range $-1.0 \leq [\mathrm{Fe/H}] \leq -2.5$ appear to have fairly uniform abundance mixes (e.g., Wheeler, Sneden, & Truran 1989), indicating the existence of substantial amounts of nuclear processing and gas mixing before the formation of these stars. The chemical compositions of stars with $[\mathrm{Fe/H}] < -2.5$ must be pursued to discover evidence for the onset of Galactic nucleosynthesis.

We are conducting an abundance study of a large sample of these extremely metal-poor stars discovered in the halo survey of Beers, Preston, & Shectman (1985, 1992), together with a "control group" of previously studied stars in the metallicity range $-2.0 < [\mathrm{Fe/H}] < -2.7$. An analysis of the overall abundance trends of 33 of these stars will be reported by Preston et al. (1994, hereafter Paper I) and McWilliam et al. (1994, hereafter Paper II). But one of the program stars, CS 22892−052, has a spectrum that is strikingly different from others of the sample. The overall extreme line weakness shows this to be a quite low-metallicity star, but in contrast the very heavy elements created by neutron captures have exceptionally strong lines. CS 22892−052 warrants special attention, and in this *Letter* we report the results of a detailed exploration of the very heavy element abundances of this star.

2. OBSERVATIONS AND ANALYSIS

Basic data for CS 22892−052, taken from Beers et al. (1992), are listed in Table 1. The entry labeled $[\mathrm{Fe/H}]_C$ is their (calibrated) Ca II K-line metallicity estimate. The combination of several of these quantities identifies this object as a very low-metallicity red giant member of the southern Galactic halo.

The spectrum for CS 22892−052 was obtained with the Las Campanas 2.5 m telescope and Shectman's Cassegrain echelle spectrograph. This instrument has refractive optics for all components except the echelle grating, and uses a 2D-FRUTTI (Shectman 1984) photon counting imaging detector. The resulting spectra are of high-resolution ($R \simeq 22{,}000$, somewhat wavelength-dependent), but rather low signal-to-noise per integration. The advantage of this instrumental system is its ability to obtain high resolution spectra of faint ($V \leq 16$) stars. We co-added 10 individual observations of CS 22892−052 to create the final $S/N \simeq 35$ spectrum; for details of this procedure please see Paper I.

In Figure 1 we show two spectral intervals of CS 22892−052, and for comparison we also show the spectrum of star CS 22878−101. These two stars have very similar intrinsic parameters: for example, CS 22878−101 has $B-V = 0.80$, $M_V \simeq -0.35$, and $[\mathrm{Fe/H}]_C = -2.89$ (Beers et al. 1992). Inspection of this figure immediately reveals some striking differences in these two spectra. Absorption features of Hδ and Fe-peak elements (e.g., Co I 4121.3 Å, Fe I 4132.1 Å, or the blend of Sc II and Ti II near 4320.8 Å) are quite similar in these stars, but all features attributable to CH or the very heavy elements ($Z > 30$) are extremely strong in CS 22892−052 while nearly undetectable in CS 22878−101 (e.g., contrast the Eu II 4129.7 Å line in these two stars). These two spectral intervals are not unique; almost all intervals in the blue and near-UV spectral regions show the same anomalies.

We used the spectrum of CS 22892−052 to determine the model atmosphere parameters and the abundances of elements with $Z < 30$ (hereafter called "lighter" elements). A detailed description of equivalent width measurements is given in Paper I, and the methods and assumptions for the atmosphere

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[4] We adopt the usual spectroscopic notation that $[X] \equiv \log_{10}(X)_{\mathrm{star}} - \log_{10}(X)_{\odot}$ for any abundance quantity X.

TABLE 1

PARAMETERS OF CS 22892−052

Quantity	Value
Basic Data	
R.A.(1950)	$22^{\rm h}14^{\rm m}18\overset{\rm s}{.}9$
Decl.(1950)	$-16°54'26''$
$l^{\rm II}$	$41\overset{\circ}{.}1$
$b^{\rm II}$	$-52\overset{\circ}{.}8$
V	13.18
$B-V$	0.78
$U-B$	0.14
$V-R$	0.48
$E(B-V)$	0.02
M_V	−0.23
Distance (pc)	4700
$[{\rm Fe/H}]_C$	−2.92
Model Atmosphere	
$T_{\rm eff}$ (K)	4725
log g	1.00
$[M/{\rm H}]$	−3.0
v_t (km s^{-1})	2.0

analysis can be found in Paper II. Here is a very brief summary. We obtained initial $T_{\rm eff}$ estimates from a calibration of the Cousins $(V-R)$ and $(B-V)$ colors. We then located the star (via its M_V and $B-V$) on the giant branch sequence of the color-magnitude diagram of the very metal-poor globular cluster M92, and used the calibration of Carbon et al. (1982) to estimate an initial gravity. We adopted $[{\rm Fe/H}]_C$ as a trial metallicity estimate, and assumed an initial microturbulent velocity of 2 km s^{-1}. An appropriate model was computed with the MARCS stellar atmosphere code (Bell et al. 1976). We then used a current version of the LTE line analysis code of Sneden (1973) to derive line-by-line abundances for each species from matches of calculated and observed equivalent widths. We iterated in the $T_{\rm eff}/\log g/[M/{\rm H}]/v_t$ parameter space to take out trends of abundance with excitation potential, equivalent width, and ionization state, to produce the final model atmosphere parameters that are listed in Table 1, and the final abundances of the lighter elements that are listed in Table 2. The abundances of these elements are weighted means of the individual line abundances; see Paper II for details of this procedure.

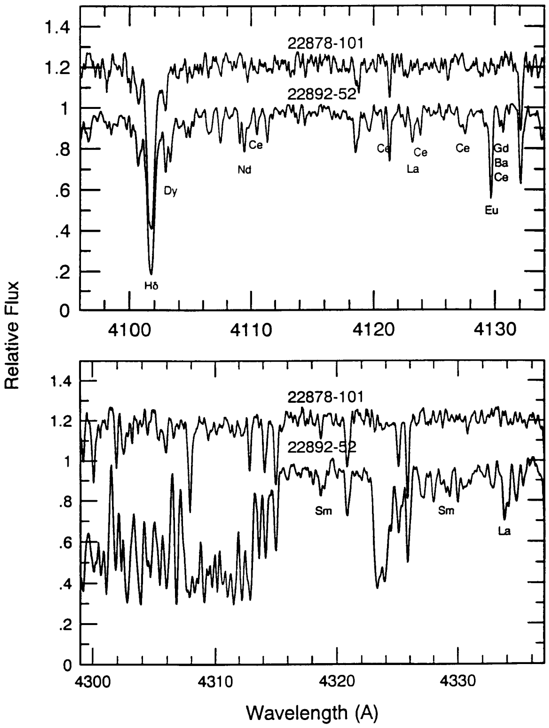

FIG. 1.—Comparison of the spectra of stars CS 22892−052 and CS 22878−101 in two small spectral intervals. The stronger transitions of the very heavy elements have been marked in the figure; all of them arise from low-excitation states of singly ionized species. Of the remaining absorption features, those that match well in the two spectra are transitions of lighter ($Z < 30$) elements, and those that are much stronger in CS 22892−052 are CH lines.

We plot the abundances of the lighter elements in the top panel of Figure 2. Because the very heavy element line strengths are so anomalously strong in CS 22892−052, we pause here to emphasize several features of the analysis of the lighter elements. First, the final model atmosphere parameters for this star are essentially identical to the initial estimates, and in Paper II we will demonstrate that the derived parameters, including abundances of all the Fe-peak elements, are virtually indistinguishable from those of CS 22878−101. Second, the ionization equilibria of Fe and Ti, both of which are represented by a large number of lines of each species, are satisfied with a single gravity value, and that gravity is consistent with the implied position on the M92 color-magnitude diagram. Third, the abundance ratios among the lighter elements are consistent with those of other halo stars of this metallicity regime. That is, within the quoted line-to-line scatter uncertainties (the σ column in Table 2), the Fe-peak elements are in their solar ratios with respect to Fe, and the α-capture elements of Mg, Ca, and Ti are enhanced by ~0.4

TABLE 2

ABUNDANCES

Species	$[X/{\rm H}]$	$[X/{\rm Fe}]$	σ	Number
C (CH)	−2.00	+1.12	0.20	...
Na I	−3.00	+0.12	0.31	2
Mg I	−2.71	+0.42	0.22	4
Al I	−3.71	−0.58	...	1
Si I	−1.90	+1.22	0.35	2
Ca I	−2.62	+0.50	0.20	11
Sc II	−3.30	−0.18	0.20	4
Ti I	−2.89	+0.24	0.20	10
Ti II	−2.93	+0.19	0.18	27
Cr I	−3.40	−0.28	0.21	5
Mn I	−3.22	−0.10	0.31	2
Fe I	−3.09	+0.04	0.21	121
Fe II	−3.16	−0.04	0.17	18
Co I	−2.86	+0.26	0.21	2
Sr II	−2.60	+0.52	0.00	2
Y II	−2.79	+0.33	0.13	7
Zr II	−2.32	+0.80	0.10	5
Ba II	−2.23	+0.89	0.09	6
La II	−2.15	+0.97	0.11	5
Ce II	−2.18	+0.94	0.18	8
Nd II	−1.82	+1.30	0.15	9
Sm II	−1.64	+1.48	0.05	3
Eu II	−1.56	+1.56	0.06	4
Gd II	−1.72	+1.40	0.10	2
Dy II	−1.33	+1.79	0.03	2
Er II	−1.63	+1.49	...	1

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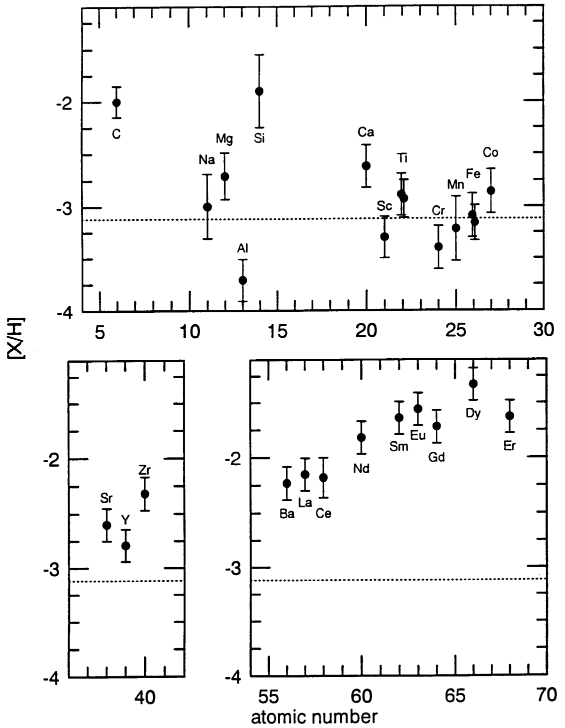

FIG. 2.—Element abundances $[X/H]$ in CS 22892−052. In each panel the horizontal dotted line marks the stellar metallicity, in the upper panel the abundances of the elements synthesized in the major nuclear fusion stages are shown. In the lower left and right panels we isolate the elements near the first and second neutron-capture peaks, respectively. Each error bar depicted here is the maximum of ±0.15 or $\pm\sigma$ (from Table 2).

dex over Fe.[5] Finally, we determined the C abundance via spectrum synthesis of the spectral region from 4290 to 4330 Å, using the atomic and molecular line list of Brown (1987). The reader is referred to Brown's extensive discussion of the normalization uncertainties of various C indicators (see also Tomkin et al. 1992), which unfortunately still may be as large as 0.3 dex; CH syntheses with this line list yield lower C abundances than do C_2 or C I lines, and thus the C overabundance derived here may be a slight underestimate. A full molecular equilibrium solution was computed including the effects of CO formation, but in practice the extreme metal poverty of the star made CO of neglible importance to the C equilibrium. The very large (+1.1 dex) relative overabundance of C confirms the visual impression of Figure 1. We also used the CH line list in an unsuccessful search for the presence of ^{13}CH features (e.g., Sneden, Pilachowski, & VandenBerg 1986) in the spectral regions near 4230 and 4370 Å. Tentatively we suggest $^{12}C/^{13}C > 20$, but a more definitive limit or detection requires a higher S/N spectrum of CS 22892−052.

We used spectrum synthesis to determine abundances for each line of the very heavy ($Z > 30$) elements. We adopted the well-determined laboratory *gf*-values for Sr, Y, Zr, Ba, Sm, Eu, and Er, and determined *gf*'s for the features of other very heavy element species from an inverted solar analysis. Details of our transition probability choices will be given in Paper II, and are consistent with the choices of Gratton & Sneden (1994). A full discussion of *gf*'s is unnecessary here, for the derived overabundances of all of these elements are very much larger than any *gf* uncertainties. Beginning with the $\sim +0.5$ dex overabundance of the first neutron-capture peak elements (lower left panel of Fig. 2), the abundance enhancements rise to over +1.5 dex among heavier elements of the second neutron capture peak. We call attention here to the large number of transitions participating in the abundance determinations of these elements, and to the excellent line-to-line agreement for each abundance. This is due not only to the strength of the very heavy element features, but also to the weakness of potential contaminating lines of lighter elements. For example, the 4435.6 Å Eu II line usually is totally masked by a strong Ca I line at that wavelength, but proved tractable for the Eu abundance analysis in CS 22892−052. Probably many more useful very heavy element transitions will be recoverable in a higher S/N spectrum of this star. For example, we think it possible that the Th II feature at 4019.1 Å is present in this spectrum, with a measured EW of 15 ± 6 mÅ. It will be important to investigate this from higher S/N spectra.

3. DISCUSSION

The star CS 22892−052 possesses the largest overabundance of very heavy elements of any very metal-poor ($[Fe/H] < -2.5$) halo star found to date; no other star approaches this level of enrichment in neutron-capture elements.[6] Among more mildly metal-poor stars, the so-called CH giants do have significant overabundances of C (and N) and the very heavy elements (Vanture 1992a, b). And, like our star CS 22892−052, the CH stars also have larger overabundances of the second neutron-capture element peak than of the first. However, in the CH stars the abundance ratios are quite different among elements of the second peak: the lighter of these elements are more abundant than the heavier ones. Averaging the abundances for all of Vanture's seven CH stars, $[(La, Ce)/(Nd, Sm)] \sim +0.4$, but this ratio in CS 22892−052 is ~ -0.4. And the average Eu overabundance of the CH stars is much less than for the other elements of the second peak, while this is one of the most overabundant elements in our star. Vanture can successfully model the CH giants with the addition of neutron-capture material created by the *s*-process, but the trend toward larger enhancements of the heavier second-peak elements in CS 22892−052 will not permit a match with any published *s*-process element distribution (e.g., Malaney 1987a, b).

We obtain a much closer match of the observed abundance ratios with *r*-process neutron-capture distributions. Within the uncertainties of both theory and observation, the very heavy element distribution of CS 22892−052 matches that of either a scaled solar-system *r*-process abundance set (Käppeler, Beer, & Wisshak 1989), or a theoretical *r*-process prediction (Cowan et al. 1987). A discussion of the details of this match is deferred to a future paper.

Perhaps the real significance of CS 22892−052 lies in the nearly complete detachment of the very heavy element abundance level from that of the lighter elements. Several abun-

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[5] The abundance of Si is very uncertain; it is determined from only two very strong ground-state lines that lie in a crowded spectral region. Observations of other higher excitation transitions of Si I, too weak to be detected on our spectra, should be pursued.

[6] HD 115444 may be a less extreme version of CS 22892−052, with $[Fe/H] \sim -2.8$ and $[\text{very heavy/Fe}] \leq +0.8$, but there is disagreement on the origin of its abundance anomalies. Griffin et al. (1992) suggest a substantial amount of *s*-processing, while Gilroy et al. (1988) argue for mainly an *r*-process origin. This star deserves a reanalysis with new high-resolution spectroscopic data.

dance surveys of very metal-poor stars have concluded that the very heavy element content (both the *r*- and *s*-process contributions) may decline precipitously in stars with [Fe/H] < −2 (e.g., see Figs. 1 and 2 of Sneden et al. 1988). The following two abundance summaries illustrate this point. From Luck & Bond (1985): for six stars with $-2.0 \geq$ [Fe/H] > -2.5, the average Eu abundance is $\langle$[Eu/Fe]$\rangle = +0.05 \pm 0.17$, with a star-to-star scatter $\sigma = 0.41$; for seven stars with [Fe/H] ≤ -2.5, $\langle$[Eu/Fe]$\rangle = -0.48 \pm 0.11$, with $\sigma = 0.29$. From Gratton & Sneden (1994): for five stars with $-1.7 \geq$ [Fe/H] > -2.3, $\langle$[Eu/Fe]$\rangle = +0.29 \pm 0.05$, with $\sigma = 0.12$; for three stars with [Fe/H] < -2.5, $\langle$[Eu/Fe]$\rangle = -0.10 \pm 0.17$, with $\sigma = 0.30$. A [Eu/Fe] decrease of approximately 0.5 dex in the more metal-poor stars is seen in both surveys (the large values of σ partly reflect real star-to-star scatter, and not simply observation and analysis defects; see, e.g., Gilroy et al. 1988). Our star, with [Eu/Fe] $\simeq +1.6$, provides a strong counter-example to this general trend. We note that the relative content of the very heavy elements also seems to be quite variable from star-to-star in our larger sample (to be discussed in Paper II), although no other star approaches the kind of overabundance seen in CS 22892−052. This existence of this star provides strong evidence for local nucleosynthesis events in the early Galactic halo.

What sort of local event created the element distribution of CS 22892−052? Mathews & Cowan (1990) use the general trend of [Eu/Fe] with [Fe/H] metallicity (particularly the apparent downturn in [Eu/Fe] for [Fe/H] < -2.5) to argue that low-mass Type II supernovae are the source of *r*-process elements in the early Galaxy. Although our star has a very large [Eu/Fe] ratio, if the synthesis of its very heavy elements was truly local (no general mixing of the very heavy elements throughout the halo ISM) then their conclusion may be still valid, but one might then expect very low metallicity stars simply to have variable fractions of the very heavy elements. The very large C abundance of CS 22892−052 offers supporting evidence. The "bulk yields" of supernovae (from several studies, beginning with Arnett 1978) generally favor the production of C more than the rest of the α elements (Ne, Mg, and especially O) as the supernova mass decreases. The nucleosynthesis yields of a 20 $M_{\odot}$ supernova (with a core mass of 6 $M_{\odot}$ core) by Thielemann, Hashimoto, & Nomoto (1990) do not resemble the abundances of our star (the C and Ca contents are far too low, the Al is too large, etc.).

There are too many gaps in the observed abundance distribution of CS 22892−052 to allow rigorous tests of supernova nucleosynthesis predictions. There are features of crucial elements (e.g., [O I] and Li I lines) not detected on our low S/N spectra, and some of our abundances (e.g., Si) are quite uncertain. The main purpose of this *Letter* is to call attention to this unique star, and to emphasize that spectra of higher S/N should be obtained to complete the abundance description. In addition to the O and Si data, the molecular CN, C_2 and CH bands should be used to derive C/N and $^{12}C/^{13}C$ ratios, in order to search for signs of internal nucleosynthesis and envelope mixing in CS 22892−052. The Rb I 7800 Å line should be looked for; the Rb/Sr ratio is a sensitive indicator of the *r*-process/*s*-process efficiency in the production of the lighter neutron-capture elements. The call for further observations of Th II 4019 Å has been given earlier; just as useful would be an attempt to detect the Pb I 3683 Å line; the combination of these two elements would set the level of original production of the heaviest elements by the progenitor of CS 22892−052, and yield a new estimate for the age of the Galactic halo.

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