THE ASTROPHYSICAL JOURNAL, 576:L141–L144, 2002 September 10
© 2002. The American Astronomical Society. All rights reserved. Printed in U.S.A.

CHEMICAL COMPOSITION OF THE CARBON-RICH, EXTREMELY METAL POOR STAR CS 29498−043: A NEW CLASS OF EXTREMELY METAL POOR STARS WITH EXCESSES OF MAGNESIUM AND SILICON[1]

WAKO AOKI,[2] JOHN E. NORRIS,[3] SEAN G. RYAN,[4] TIMOTHY C. BEERS,[5] AND HIROYASU ANDO[2]

Received 2002 June 17; accepted 2002 July 20; published 2002 August 8

ABSTRACT

We analyze a high-resolution, high signal-to-noise ratio spectrum of the carbon-rich, extremely metal poor star CS 29498−043, obtained with the Subaru Telescope High Dispersion Spectrograph. We find its iron abundance is extremely low ([Fe/H] = −3.7), placing it among the few stars known with [Fe/H] ≤ −3.5, while Mg and Si are significantly overabundant ([Mg/Fe] = +1.8 and [Si/Fe] = +1.1) compared with stars of similar metallicity without carbon excess. Overabundances of N and Al were also found. These characteristics are similar to the carbon-rich, extremely metal poor star CS 22949–037. Although the sample is small, our discovery of CS 29498−043 suggests the existence of a class of extremely metal poor stars with large excesses of C, N, Mg, and Si.

Subject headings: nuclear reactions, nucleosynthesis, abundances — stars: abundances — stars: carbon — stars: individual (CS 29498−043) — stars: Population II

1. INTRODUCTION

The most metal-poor stars in the Galactic halo are believed to contain the material ejected from the first generations of stars. To investigate the nucleosynthetic yields of supernovae, the chemical compositions of a number of extremely metal poor stars have been studied recently (e.g., McWilliam et al. 1995; Ryan, Norris, & Beers 1996). Some objects show distinct chemical characteristics considered to result from nucleosynthesis in a single massive star and its supernova.

An extreme example is CS 22949−037. McWilliam et al. (1995) found this object to be an extremely metal poor ([Fe/H] ∼ −4.0)[6] giant with α-element excesses. Norris, Ryan, & Beers (2001) confirmed the excesses of C, Mg, and Si, compared with iron and discovered an extremely large enhancement of nitrogen ([N/Fe] = +2.7). Depagne et al. (2002) found significantly large excesses of oxygen and sodium ([O/Fe] = +2.0 and [Na/Fe] = +2.1). Comparisons with model predictions for the yields of supernovae (e.g., Woosley & Weaver 1995; Fryer, Woosley, & Heger 2001; Heger & Woosley 2002) with zero heavy elements have been made to explain its abundance characteristics.

During our study of very metal poor stars using the University College London coudé échelle spectrograph (UCLES) at the Anglo-Australian Telescope (AAT; e.g., Norris, Ryan, & Beers 1996), we found that the carbon-rich object CS 29498−043 exhibited strong Mg lines. To conduct a more detailed study, we obtained a high-resolution spectrum with the High Dispersion Spectrograph (HDS) of the Subaru Telescope (Noguchi et al. 2002). Our analysis shows that CS 29498−043 is an extremely iron deficient giant ([Fe/H] = −3.7) that, contrary to most stars of similar metallicity, exhibits large excesses of C, N, Mg, and Si compared with Fe. These characteristics are similar to, but more extreme than, those of CS 22949−037.

In this Letter we report on the composition of the carbon-rich, extremely metal poor star CS 29498−043. Its CH and CN bands are as strong as another carbon-enhanced, extremely metal poor star CS 22957−027 ([Fe/H] ∼ −3.4; Norris, Ryan, & Beers 1997b; Bonifacio et al. 1998), which we also analyzed using a spectrum obtained with HDS for comparison.

2. OBSERVATION AND MEASUREMENTS

High-resolution spectra of CS 29498−043 and CS 22957−027 were obtained with HDS in 2001 July. They cover the wavelength range 3550–5250 Å, with resolving powers R = 50,000 and 60,000, respectively. Data reduction was performed in the standard way within the IRAF environment.[7] For the 7200 and 4592 s exposures for CS 29498−043 and CS 22957−027, the detected photons number 1640 and 3780 per 0.013 Å pixel at 4320 Å and 3260 and 5220 per 0.0155 Å pixel at 5180 Å, respectively.

The spectra around 5200 Å are shown in Figure 1, where the Mg I triplet lines of CS 29498−043 are seen to be much stronger than those in CS 22957−027, while other metallic features, such as Fe I and Cr I, have similar strengths in both spectra. This suggests a large enhancement of Mg compared with Fe and other metals in CS 29498−043, although their atmospheric parameters (e.g., effective temperature) must be accounted for. The C$_2$ Swan band at 5165 Å appears in both spectra, indicating that both stars are carbon-rich.

Equivalent widths of absorption lines for 10 metals (12 ionization species) were measured by fitting Gaussian profiles. Wavelengths, excitation potentials, transition probabilities, and equivalent widths will be reported separately (W. Aoki et al. 2002, in preparation).

Heliocentric radial velocities have been measured from a large number of clean Fe I lines. The velocities of CS 29498−043 and CS 22957−027 are $V_r = -32.6 \pm 0.29$ km s^{-1} (2001 July 26, JD = 2,452,117) and $V_r = -61.6 \pm 0.22$ km s^{-1} (2001 July

---

[1] Based on data collected at the Subaru Telescope, which is operated by the National Astronomical Observatory of Japan.

[2] National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan; aoki.wako@nao.ac.jp, ando@optik.mtk.nao.ac.jp.

[3] Research School of Astronomy and Astrophysics, Australian National University, Mount Stromlo Observatory, Cotter Road, Weston Creek, Canberra, ACT 2611, Australia; jen@mso.anu.edu.au.

[4] Department of Physics and Astronomy, Open University, Walton Hall, Milton Keynes MK7 6AA, UK; s.g.ryan@open.ac.uk.

[5] Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824-1116; beers@pa.msu.edu.

[6] $[\mathrm{A/B}] = \log (N_\mathrm{A}/N_\mathrm{B}) - \log (N_\mathrm{A}/N_\mathrm{B})_\odot$, and $\log \epsilon_\mathrm{A} = \log (N_\mathrm{A}/N_\mathrm{H}) + 12$ for elements A and B.

[7] IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

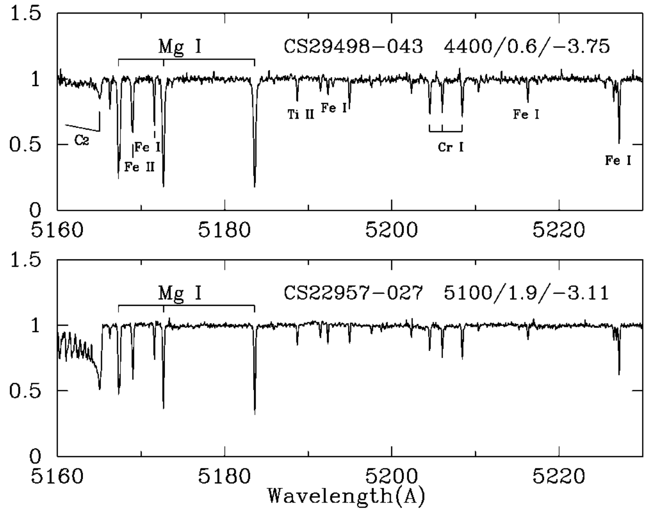

FIG. 1.—Observed spectra of CS 29498−043 (*upper panel*) and CS 22957−027 (*lower panel*). Five-pixel rebinning has been applied to these spectra. The species that contribute to the absorption features are shown; $T_{\rm eff}$, log g, and [Fe/H] are also presented.

23, JD = 2,452,114), respectively. The radial velocity of CS 29498−043 was also measured from the AAT/UCLES spectrum obtained on 2000 September 14 (JD = 2,451,802) to be $V_r = -32.5 \pm 0.18$ km s^{-1}; there is no evidence of binarity. There is also no indication of binarity for CS 22949−037 (Depagne et al. 2002). Further monitoring of radial velocities will provide a valuable constraint on models of the formation of these objects.

3. ABUNDANCE ANALYSIS

Effective temperatures ($T_{\rm eff}$) were estimated from the $(B-V)_0$ and $(V-K)_0$ colors in Table 1. The B and V photometry is from Norris, Ryan, & Beers (1999) and Beers, Preston, & Shectman (1992) for CS 29498−043 and CS 22957−027, respectively, and K was taken from the interim Two Micron All Sky Survey Point Source Catalog (Skrutskie et al. 1997). Interstellar reddening was estimated from the Schlegel, Finkbeiner, & Davis (1998) maps.

The effective temperature scale of carbon-rich stars by Aoki et al. (2002a) implied CS 29498−043 to be 4600 K from $(B-V)_0$, while 4500 K is derived from $(V-K)_0$ using the scale of Alonso, Arribas, & Martínez-Roger (1999). Initially, we adopted $T_{\rm eff} = 4600$ K for the analysis of the Fe I and Fe II lines. However, after determining the other atmospheric parameters, we obtained lower abundances from higher excitation lines, suggesting that $T_{\rm eff} = 4600$ K may be too high. Ultimately, we adopted $T_{\rm eff} = 4400$ K, but considering the ambiguity, we also performed analyses for $T_{\rm eff} = 4600$ K [from $(B-V)_0$] and for $T_{\rm eff} = 4250$ K (at which the dependence of the derived Fe abundance on excitation potential almost vanishes).

The effective temperature of CS 22957−027 estimated from $(B-V)_0$ is 5100 K, which agrees with the temperature from $(V-K)_0$. The effective temperature derived from $(B-V)_0$ by Norris et al. (1997b) and Bonifacio et al. (1998) is about 4850 K, but the effect of molecular absorption (e.g., CH bands) in the blue range was not included in those works. The offset estimated from the scale of Aoki et al. (2002a) is about 200 K and is the likely reason for the discrepancy between the values. Norris et al. (1997b) also performed an analysis for $T_{\rm eff} = 5100$ K as an alternative possibility, taking account of the carbon excess. CS 22957−027 was studied also by Preston & Sneden (2001), who included the effect of molecular absorption on the broadband colors and adopted $T_{\rm eff} = 5050$ K. Their value agrees well with the one adopted here.

Using model atmospheres from Kurucz (1993) at the adopted effective temperatures, we performed abundance analyses in the standard manner for the measured equivalent widths. Surface gravities (g) were determined from the ionization balance between Fe I and Fe II, and the microturbulence ($v_{\rm tur}$) was determined from the Fe I lines by demanding no dependence of the derived abundance on equivalent widths.

We found that the Fe abundance of CS 29498−043 is very low ([Fe/H] $\lesssim -3.5$, i.e., log ϵ(Fe) $\lesssim 4.0$), while the Mg overabundance is quite large ([Mg/Fe] $\gtrsim 1.5$, i.e., log ϵ(Mg) $\gtrsim 5.5$). This means that Mg is an important electron source in the line-forming layer of the stellar atmosphere, and the effect of its overabundance must be included in the analysis. We iterated the abundance analysis so that the derived Mg abundance is consistent with the one assumed in the calculation. The effect of the Mg excess on the determination of the surface gravity is large ($\Delta \log g = 0.4$ dex); if a higher Mg abundance is assumed, the electron pressure is higher, and the ionization balance between Fe I and Fe II demands a lower gravity. After taking into account a redetermination of the surface gravity, the effect of the Mg overabundance ([Mg/Fe] = +1.8) on the final abundances of the elements examined here is not significant (e.g., Δ[Fe/H] < 0.1 dex). A high overabundance of Si ([Si/Fe] = +1.1) was also found, but its effect on the analysis is negligible.

Spectrum synthesis was applied to the C_2, CN, ^{12}CH, and ^{13}CH bands to determine the carbon and nitrogen abundances and the carbon isotope ratio. Molecular data were from Aoki et al. (2002b). For CS 29498−043, we tried the analysis for the range $0.5 \leq$ [O/Fe] ≤ 2.5, mindful of the large oxygen excess found in CS 22949−037 (Depagne et al. 2002), which may also apply to the present star. We found that the carbon abundance of CS 29498−043 derived from the C_2 Swan 0–0 band is [^{12}C/Fe] = +1.9 when [O/Fe] = 2.0 is assumed, and it changes by about 0.2 dex over the assumed range of [O/Fe]. We have adopted these results for the carbon abundance and its error due to the uncertainty of the oxygen abundance. The nitrogen abundance of CS 29498−043 was determined from the 0–1 band of the 4215 Å CN violet system to be [N/Fe] = +2.3. A similar analysis was applied to CS 22957−027; [^{12}C/Fe] = +2.4 and [N/Fe] = +1.6 were derived and found to be insensitive to the assumed oxygen abundance.

Carbon isotope ratios are estimated from the three CH $B-X$ lines around 4000 Å. Line positions were calculated using the molecular constants of Kępa et al. (1996). The wavelengths of the ^{13}CH lines were adjusted by fitting the synthetic spectrum to the observed one for CS 22957−027 and were then applied to

TABLE 1

PHOTOMETRIC DATA AND STELLAR PARAMETERS

Object	V	B	$(B-V)_0$	K	$(V-K)_0$	$T_{\rm eff}$	log g	$v_{\rm micro}$	[Fe/H]
CS 29498−043	13.72	14.80	0.99	10.95	2.50	4400	0.6	2.3	−3.75
CS 22957−027	13.59	14.36	0.74	11.61	1.92	5100	1.9	1.4	−3.11

TABLE 2

ABUNDANCE RESULTS

	CS 29498−043				CS 22957−027			
ELEMENT	[X/Fe]	log ϵ_{el}	*n*	σ	[X/Fe]	log ϵ_{el}	*n*	σ
^{12}C (C$_2$)	+1.90	6.70	…	0.29	+2.37	7.80	…	0.24
N (CN)	+2.28	6.50	…	0.40	+1.62	6.45	…	0.35
Mg I	+1.81	5.64	5	0.24	+0.69	5.15	3	0.20
Al I	+0.34	3.08	1	0.36	−0.77	2.60	1	0.33
Si I	+1.07	4.88	1	0.17	…	…	…	…
Ca I	+0.11	2.71	1	0.19	+0.14	3.37	1	0.17
Sc II	+0.13	−0.52	2	0.34	…	…	…	…
Ti I	+0.12	1.31	3	0.10	+0.30	2.12	3	0.11
Ti II	+0.32	1.51	8	0.30	+0.41	2.23	6	0.20
Cr I	−0.32	1.62	2	0.10	−0.21	2.36	2	0.11
Mn I	−0.68	1.1	1	0.37	−0.41	2.0	1	0.48
Fe I ([Fe/H])	−3.75	3.75	30	0.26	−3.12	4.38	25	0.15
Fe II ([Fe/H])	−3.75	3.75	4	0.33	−3.11	4.39	4	0.24
Ni I	…	…	…	…	−0.25	2.88	4	0.26
Sr II	−0.35	−1.18	1	0.35	−0.56	−0.76	1	0.40
Ba II	−0.45	−1.98	2	0.20	−1.23	−2.13	2	0.21
^{12}C/^{13}C	6 ± 2	…	…	…	8 ± 2	…	…	…

CS 29498−043. The ^{12}C/^{13}C ratio estimated for CS 22957−027 is 8 ± 2, which agrees reasonably with the value ^{12}C/^{13}C = 10 derived by Norris et al. (1997b). The ratio ^{12}C/^{13}C = 6 ± 2 was derived for CS 29498−043. Although this ratio is formally lower than that of CS 22957−027, we cannot insist on the reality of the difference. Also, we cannot conclude that the ^{12}C/^{13}C of CS 29498−043 is higher than the equilibrium value of the CNO cycle (∼4), while that of CS 22957−027 is obviously higher than the equilibrium value.

A standard analysis was performed for most elements using measured equivalent widths. Hyperfine splitting and isotope shifts were included in the analysis of Ba II lines, using the line list of McWilliam (1998) and adopting the isotope ratios of the solar system *r*-process component. The effect on the derived abundance is small ($\lesssim$0.1 dex) because the Ba lines are weak in these stars. The Al and Mn abundances were determined by spectrum synthesis from the Al I 3961 Å and Mn I 4030 Å lines because these lines are contaminated by ^{13}CH and ^{12}CH lines ($B-X$ band), respectively. Since these blends involve CH doublets, the strength of each blending CH line can be estimated well from the other component. The results of the abundance analysis are given in Table 2.

To estimate the random errors, we first calculated the dispersion of the abundances for Fe I lines in each star. We assumed the random error in *gf*-values to be 0.1 dex and added it in quadrature to the above dispersion. The final random error in the mean adopted abundance for each element was evaluated by dividing by $n^{1/2}$ (where n is the number of lines used in the analysis, given in Table 2).

Errors arising from uncertainties of the atmospheric parameters were evaluated, for CS 22957−027, using $\sigma(T_{\rm eff})$ = 100 K, $\sigma(\log g)$ = 0.5, and $\sigma(v_{\rm tur})$ = 0.5 km s^{-1}. For CS 29498−043, whose effective temperature is more uncertain as noted above, we also performed the abundance analyses assuming $T_{\rm eff}$ = 4600 and 4250 K instead of the temperature $T_{\rm eff}$ = 4400 K adopted above. We redetermined the surface gravity, metallicity, and microturbulence and derived the elemental abundances for each effective temperature. We adopted the differences of the abundances derived from the three analyses as the errors due to the uncertainty of effective temperature for CS 29498−043. The errors arising from uncertainties of its surface gravity and microturbulence were evaluated using $\sigma(\log g)$ = 0.5 and $\sigma(v_{\rm tur})$ = 0.5 km s^{-1}.

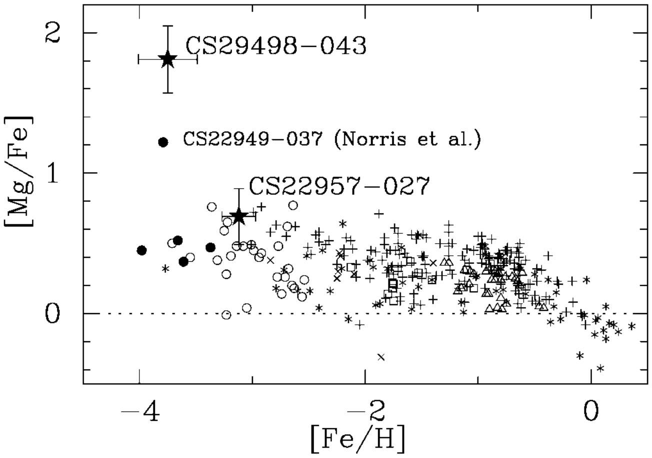

FIG. 2.—[Mg/Fe] as a function of [Fe/H]. Stars indicate values for CS 29498−043 and CS 22957−027 derived in the present work. Filled circles are adopted from Norris et al. (2001), and others are from references therein.

Finally, we derived the total uncertainty by adding in quadrature the individual errors, and we list them in Table 2. The error due to the uncertainty of the oxygen abundance assumed in the analysis is included in the total uncertainty of the carbon abundance of CS 29498−043.

Corrections for the non-LTE are not included in the present analysis. However, their effect is expected to be systematic, and the following discussion, based on the relative abundances between our objects and other metal-deficient stars, is not significantly affected.

4. DISCUSSION AND CONCLUDING REMARKS

Our analysis shows that CS 29498−043 is an extremely metal poor ([Fe/H] = −3.75) star with a large excess of C, N, Mg, and Si. These characteristics are similar to those of CS 22949−037 (McWilliam et al. 1995; Norris et al. 2001; Norris et al. 2002). In Figure 2, their [Mg/Fe] values are shown as a function of [Fe/H], along with others from previous works compiled by Norris et al. (2001). The [Mg/Fe] of CS 29498−043 is clearly much higher than the average for other stars with similar [Fe/H] and is even higher than the already extreme CS 22949−037. The [Mg/Fe] of CS 22957−027 follows the trend of the stars with similar [Fe/H], as studied by Norris et al. (1997b) and Bonifacio et al. (1998).

Figure 3 shows the abundance differences ([X/Fe] − ⟨[X/Fe]⟩) for CS 29498−043 and CS 22949−037 (Norris et al. 2001) relative to the average values of the four stars CD −24 17504, CD −38 254, CS 22172−002, and CS 22885−096 studied by Norris et al. (2001), as a function of atomic number. Excesses of C, N, Mg, and Si clearly appear in both CS 29498−043 and CS 22949−037, while there is no clear evidence of departure of the relative abundances from zero for Sc–Ni. This suggests that similar nucleosynthesis processes contributed to the abundance patterns of these two stars. The high [Mg/Fe] and [Si/Fe] values presumably indicate that the heavy elements from which these two stars formed came from supernovae whose outer layers (where C and Mg are produced) escaped, but where relatively little material escaped from nearer the iron core. Clearly, the nucleosynthesis mechanism is distinct from that in the asymptotic giant branch stars responsible for high C and *s*-process abundances in some, but not all, carbon-enhanced, metal-poor stars.

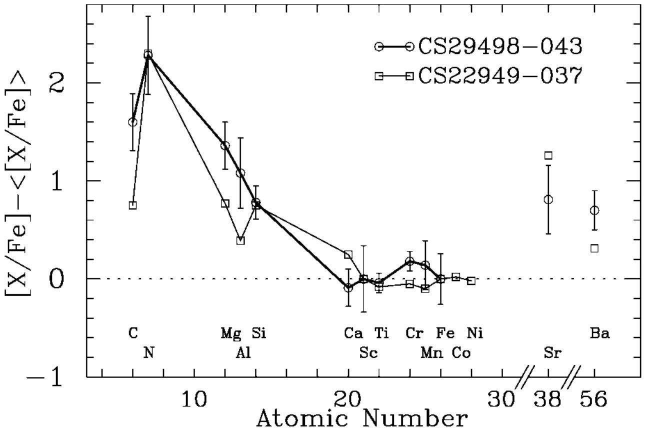

FIG. 3.—Relative abundances of elements in CS 29498−043 and CS 22949−037, with respect to the average values of the four stars studied by Norris et al. (2001) other than CS 22949−037, as a function of atomic number. Nitrogen abundance of the reference stars is assumed to be $[\mathrm{N/Fe}] = 0$. Elemental abundances of CS 22949-037 is adopted from Norris et al. (2002) for nitrogen and from Norris et al. (2001) for the rest.

While the excesses of Si in CS 29498−043 and CS 22957−027 are similar, the excess of Mg in CS 29498−043 is noticeably larger than that of CS 22949−037; the difference in [Mg/Fe] is 0.59 dex, significant at a $2.1\,\sigma$ level when we adopt the results of Norris et al. (2001) for CS 22949−037. (The significance is $1.8\,\sigma$ if we adopt the result of Depagne et al. 2002.) The Al abundance of CS 29498−043 is also higher than that of CS 22949−037, although the uncertainty of the Al abundance is large owing to the contamination from the CH line and the strong (but uncertain) non-LTE effect for this element (e.g., Baumüller & Gehren 1997). In addition to the small excess of the relative Al abundance, a large enhancement of Na was also found in CS 22949−037 (Depagne et al. 2002). Studies of odd-*Z* elements such as Na and K in CS 29498−043 are desirable to investigate the nucleosynthesis processes that produced its abundance pattern. Measurement of its oxygen abundance, which has a large excess in CS 22949−037 (Depagne et al. 2002), is also of importance.

The fraction of stars which are carbon-enhanced increases with decreasing metallicity (Rossi, Beers, & Sneden 1999). High-resolution spectroscopy has been carried out for more than 10 carbon-rich stars with $-3.0 < [\mathrm{Fe/H}] < -2.0$. While some show large excesses of *s*-process elements (e.g., Aoki et al. 2002b), others show no such excess (Aoki et al. 2002a). No other carbon-rich object with such large excesses of Mg and Si as CS 29498−043 is known (W. Aoki, et al. 2002, in preparation). However, only four objects with $[\mathrm{C/Fe}] \gtrsim 1.0$ are known in the metallicity range of $[\mathrm{Fe/H}] < -3.0$. One is the carbon- and nitrogen-enhanced star CS 22957−027 studied by Norris et al. (1997b), Bonifacio et al. (1998), and in the present work. Another is the *r*-process–enhanced star CS 22892−052 (Sneden et al. 1996). The excesses of carbon and nitrogen of that object ($[\mathrm{C/Fe}] \sim [\mathrm{N/Fe}] \sim 1.0$) are much smaller than those of CS 22957−027, while the abundance pattern of the elements with $12 \lesssim Z \lesssim 28$ is similar to those of the other objects with normal carbon abundances (McWilliam et al. 1995; Norris, Ryan, & Beers 1997a).

The other two known carbon-rich stars with $[\mathrm{Fe/H}] \lesssim -3$ are CS 22949−037 and CS 29498−043. These objects have lower iron abundances ($[\mathrm{Fe/H}] < -3.5$) than CS 22957−027 and CS 22892−052 ($[\mathrm{Fe/H}] \sim -3.0$) and also have large excesses of Mg and Si, as shown here. Although the sample is too small to permit definitive conclusions, the similarity of CS 22949−037 and CS 29498−043 suggests that other extremely metal poor ($[\mathrm{Fe/H}] \lesssim -3.5$) stars with carbon excess may also show a large enhancement of Mg and Si. Since the ratio of carbon-rich objects seems to increase with decreasing metallicity, a number of objects similar to these two stars perhaps exist. Further spectroscopic studies of candidate extremely metal poor stars with strong CH and CN features are essential to investigate the nucleosynthesis processes in zero (or very low) metallicity stars in the early Galaxy. Comparisons with theoretical predictions of yields ejected from supernovae will be presented separately in a future paper; here we emphasize the importance of the discovery of CS 29498−043, which suggests the existence of a class of extremely metal poor stars with excesses of C, N, Mg, and Si.

The authors are grateful for fruitful discussions of these results with A. Chieffi, A. Heger, M. Limongi, and S. Woosley. T. C. B. acknowledges partial support for this work from grants AST 00-98549 and AST 00-98508, awarded by the National Science Foundation.

REFERENCES

Alonso, A., Arribas, S., & Martínez-Roger, C. 1999, A&AS, 140, 261
Aoki, W., Norris, J. E., Ryan, S. G., Beers, T. C., & Ando, H. 2002a, ApJ, 567, 1166
Aoki, W., Norris, J. E., Ryan, S. G., Beers, T. C., Ando, H., & Tsangarides, S. 2002b, ApJ, in press
Baumüller, D., & Gehren, T. 1997, A&A, 325, 1088
Beers, T. C., Preston, G. W., & Shectman, S. A. 1992, AJ, 103, 1987
Bonifacio, P., Molaro, P., Beers, T. C., & Vladilo, G. 1998, A&A, 332, 672
Depagne, E., et al. 2002, A&A, in press
Fryer, C. L., Woosley, S. E., & Heger, A. 2001, ApJ, 550, 372
Heger, A., & Woosley, S. E. 2002, ApJ, 567, 532
Kępa, R., Para, A., Rytel, M., & Zachwieja, M. 1996, J. Mol. Spectrosc., 178, 189
Kurucz, R. L. 1993, CD-ROM 13, ATLAS9 Stellar Atmosphere Programs and 2 km s^{-1} Grid (Cambridge: SAO)
McWilliam, A. 1998, AJ, 115, 1640
McWilliam, A., Preston, G. W., Sneden, C., & Searle, L. 1995, AJ, 109, 2757
Noguchi, K., et al. 2002, PASJ, submitted
Norris, J. E., Ryan, S. G., & Beers, T. C. 1996, ApJS, 107, 391
Norris, J. E., Ryan, S. G., & Beers, T. C. 1997a, ApJ, 488, 350
———. 1997b, ApJ, 489, L169
———. 1999, ApJS, 123, 639
———. 2001, ApJ, 561, 1034
Norris, J. E., Ryan, S. G., Beers, T. C., Aoki, W., & Ando, H. 2002, ApJ, 569, L107
Preston, G. W., & Sneden, C. 2001, AJ, 122, 1545
Rossi, S., Beers, T. C., & Sneden, C. 1999, in ASP Conf. Ser. 165, The Third Stromlo Symp., The Galactic Halo, ed. B. K. Gibson, T. S. Axelrod, & M. E. Putman (San Francisco: ASP), 268
Ryan, S. G., Norris, J. E., & Beers, T. C. 1996, ApJ, 471, 254
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Skrutskie, M. F., Lysaght, M. G., & Weinberg, M. D. 1997, in The Impact of Large Scale Near-IR Sky Surveys, ed. F. Garzon, N. Epchtein, A. Omont, B. Burton, & P. Persi (Dordrecht: Kluwer), 117
Sneden, C., McWilliam, A., Preston, G. W., Cowan, J. J., Burris, D. L., & Armosky, B. J. 1996, ApJ, 467, 819
Woosley, S. E., & Weaver, T. A. 1995, ApJS, 101, 181