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Chemical Compositions of Four Metal-poor Giant Stars

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ABSTRACT. We present the chemical compositions of four K giants (CS 22877-1, CS 22166-16, CS 22169-35, and BS 16085−0050) that have [Fe/H] in the range −2.4 to −3.1. Metal-poor stars with [Fe/H] < −2.5 are known to exhibit considerable star-to-star variations of many elements. This quartet confirms this conclusion. CS 22877-1 and CS 22166-16 are carbon-rich. There is significant spread of [α/Fe] within our samples, where [α/Fe] is computed from the mean of the [Mg/Fe] and [Ca/Fe] ratios. BS 16085−0050 is remarkably α-enriched with a mean [α/Fe] of +0.7, but CS 22169-35 is α-poor. The aluminum abundance also shows a significant variation over the sample. A parallel and unsuccessful search among high-velocity late-type stars for metal-poor stars is described.

1. INTRODUCTION

Chemical compositions of metal-poor stars have long been used to probe the history of the early Galaxy. As the number of very metal-poor stars having a well-determined chemical composition has increased, it has become apparent that the metallicity, usually represented by the iron abundance [Fe/H], is not sufficient to predict the abundances of other elements; a real star-to-star scatter in abundance ratios appears for many elements among stars more metal-poor than [Fe/H] of about −2. For stars in the [Fe/H] range −2 to +0.3, the various ratios show almost no "cosmic" scatter. In the light of the cosmic scatter shown by very metal-poor stars, it is important to analyze as large a sample of such stars as possible, in order to characterize fully the extent of the scatter. This paper represents a modest contribution to that end by presenting abundance analyses of four K giants with [Fe/H] ∼ −2.4 to −3.1 and by describing an as yet unsuccessful search for late-type metal-poor stars in a list of stars with high tangential velocity.

2. OBSERVATIONS

A program of medium-resolution spectroscopy was undertaken to identify metal-poor field stars from Lee's (1984) list of stars with tangential velocities estimated to exceed 100 km s^{-1}. Lee compiled his lists from Lowell proper motions (Giclas, Burnham, & Thomas 1971) and an estimate of the parallax (trigonometric or spectroscopic). We elected to concentrate on stars of spectral type K because major surveys of metal-poor stars have largely been restricted to earlier spectral types (cf. Carney et al. 1996). Stars of spectral type K provide opportunities to measure aspects of a star's chemical composition not readily determinable from warmer stars. The stars observed with medium resolution are presented in Table 1. Estimates of the *B* or *V* magnitude and spectral type are taken from SIMBAD. The radial velocity is measured from our spectra (see below). In addition to stars from Lee's sample, we observed three stars from the HK Proper Motion Survey undertaken by Beers, Preston, & Schectman (1985, 1992).

The Cassegrain spectrograph at the 2.3 m Vainu Bappu Telescope at Kavalur (Prabhu, Anupama, & Surendiranath 1998) was used for the spectroscopic survey. With the chosen grating of 1200 grooves mm^{-1} and a Tektronix 1024 × 1024 24 μm pixel CCD, the intermediate dispersion was 1.3 Å pixel^{-1}. The bright K subgiant (spectral type K1 IV) star HR 4182 was observed as radial velocity standard and also as a near–solar-metallicity representative.

These spectra enabled us to measure radial velocities (Table 1) to an accuracy of about ±18 km s^{-1} using the cross-correlation task FXCORR contained in IRAF software. Our velocities are in fair agreement with the few previously published values located through SIMBAD (see footnotes to Table 1). From

TABLE 1
BASIC DATA FOR SAMPLE STARS

Star	V or B[a]	Spectral Type	V_{rad}[b,c] (km s^{-1})
CS 22166-16	12.7	...	−212
CS 22169-35	12.9	...	+12
G6-44	10.6	K0	−16
G8-30	11.7	K3	−62
G191-38	13.3*	K5	−35
G99-24	10.8	K4	+62
G106-25	10.9	K4	−58
G104-22	12.4*	K2	−83
G111-22	9.6	K2	+30
G111-28	10.4	K0	−50
G111-40	12.6*	K3	+30
G115-1	12.5	K0	+60
G252-26	10.6	K3	+31
G41-29	15.4*	K1	− 34
G115-66	10.5	K0	+36
G53-24	11.7	K2	+72
G253-37	10.7	K4	−17
G122-30	11.2	K	−71
BS 16085−0050	12.1	...	−72
CS 22877-1	...	...	+165
CS 22877-11	13.9	...	...
CS 22877-51	14.2*	...	+285

[a] The entries marked by * are B magnitudes.
[b] The radial velocities measured by Beers et al. 1992 for CS stars are −215, +2, +169, +215, and 276 km s^{-1} in the order of their appearance in Table 1.
[c] The radial velocity value of −69 km s^{-1} was reported for G106-25 by Ryan & Norris 1991.

inspection of the spectra, it was obvious that five stars from Table 1 are extremely metal-poor: CS 22166-16, 22169-35, 22877-1, 22877-11, and 22877-51. A metal deficiency for these stars was expected from the preliminary estimates of metallicity assigned by Beers et al. (1992). CS 22877-11 was the subject of a detailed abundance analysis reported by McWilliam et al. (1995) who gave the iron deficiency as [Fe/H] = −2.9. Strömgren photometry (Schuster et al. 1996) showed CS 22877-51 to be metal-poor ([Fe/H] = −2.45). Lee's star G53-24 is given [Fe/H] = 0.18 by Ryan & Norris (1991).

The three very metal-poor stars from the Kavalur survey with BS 16085−0050 from Anthony-Twarog et al. (2000) were selected for an abundance analysis. They were observed with the Apache Point Observatory's 3.5 m telescope and the vacuum-sealed echelle spectrograph. It uses a 31.6 line mm^{-1} echelle grating with a prism cross-disperser. The 2048 × 2048 SITe CCD has 24 μm pixels, resulting in a 2 pixel resolving power near 38,000. Owing to the close spacing of the orders on the CCD, it is necessary to employ nonstandard reduction methods. The most significant difference is the use of a hot star instead of a lamp as a flat. As a measure of the quality of the spectra, we note that the signal-to-noise ratio (per pixel) in the continuum near 6700 Å was about 70 (CS 22166-16), 60 (CS 22169-35), 75 (CS 22877-1), and 90 (BS 16085−0050).

3. ABUNDANCE ANALYSIS

Inspection of the high-resolution spectra confirmed that the observed stars are very metal-poor. Hydrogen lines appeared normal, with no indication of emission. Our abundance analysis was an entirely standard procedure, as described for example in our papers on the RV Tauri variables (cf. Giridhar, Lambert, & Gonzalez 2000). A 1997 version of the spectrum synthesis code MOOG (Sneden 1973) was used with model atmospheres drawn from the grid computed by Kurucz (1993). Lines of Fe I and Fe II were used to derive the atmospheric parameters: effective temperature T_{eff}, surface gravity g, and the microturbulent velocity ξ_t. The requirement that the Fe abundance derived from Fe I lines be independent of excitation potential and equivalent width were used to derive T_{eff} and ξ_t, respectively. Then, the requirement that Fe I and Fe II lines return the same abundance was used to derive log g. This use of an ionization equilibrium was verified using the Ti I and Ti II lines. Given the number of lines and the accuracy of the equivalent widths (5%–10%), we consider the uncertainties for these quite similar stars to be about ±150 K in T_{eff}, ±0.25 in log g, and ±0.2 km s^{-1} in ξ_t. The iron abundance is determined to about ±0.2 dex. Final results for the atmospheric parameters are given in Table 2. Inspection of the abundances derived for the individual stars (Table 3) show that the ionization equilibrium of Ti and Fe is satisfied with very similar parameters; the abundance differences from Ti I and Ti II lines are equal to those from the Fe I and Fe II lines to within 0.15 dex for all stars.

TABLE 2
STELLAR PARAMETERS DERIVED FROM THE FE LINE ANALYSES

Star	UT Date	Model[a] T_{eff}, log g, [Fe/H]	ξ_t (km s^{-1})	Fe I[b] log ϵ	Fe I[b] n	Fe II log ϵ	Fe II n
CS 22877-1	2000 Dec 31	5000, 1.5, −2.8	2.3	4.69 ± 0.18	55	4.63 ± 0.20	10
CS 22166-16	1999 Dec 31	5250, 2.0, −2.4	2.2	5.11 ± 0.19	33	5.06 ± 0.22	8
CS 22169-35	2000 Jan 5	4500, 1.0, −2.8	2.6	4.65 ± 0.17	34	4.66 ± 0.11	5
BS 16085–0050	2000 Mar 24	4750, 1.0, −3.1	2.3	4.36 ± 0.17	30	4.45 ± 0.15	9

[a] T_{eff} in K, log g in cgs, [Fe/H] in dex.
[b] log ϵ is the mean abundance relative to H (with log N_H = 12.00). The solar value of log ϵ(Fe) is 7.51. The standard deviations of the means, as calculated from the line-to-line scatter, are given. n is the number of considered lines.

TABLE 3
Elemental Abundances for CS 22877-1, CS 22166-16, CS 22169-35, and BS 16085−0050

Species	log $\epsilon_\odot$	CS 22877-1			CS 22166-16			CS 22169-35			BS 16085−0050		
		[X/H]	n	[X/Fe]	[X/H]	n	[X/Fe]	[X/H]	n	[X/Fe]	[X/H]	n	[X/Fe]
C I	8.55	−1.05	syn	+1.80	−1.40	syn	+1.02	−2.45	syn	+0.40	≤−3.6	syn	≤−0.5
Na I	6.33	−3.31 ± 0.03	2	−0.47	−2.05 ± 0.20	2	+0.37	−3.56 ± 0.10	2	−0.70	−2.99 ± 0.06	2	−0.13
Mg I	7.58	−2.70 ± 0.15	5	+0.14	−1.74 ± 0.22	4	+0.68	−2.86 ± 0.12	4	+0.01	−2.23 ± 0.22	5	+0.88
Al I	6.47	−2.70 ± 0.07	2	+0.14	…	…	…	−3.61 ± 0.39	2	−0.76	−3.21 ± 0.08	2	−0.10
Si I	7.55	−2.76	1	+0.08	−2.20	1	+0.22	−3.11 ± 0.60	2	−0.26	−1.88 ± 0.29	2	+1.23
Ca I	6.35	−2.53 ± 0.06	6	+0.31	−1.92 ± 0.15	7	+0.50	−2.77 ± 0.11	7	+0.08	−2.56 ± 0.14	7	+0.55
Sc II	3.13	−2.71	1	−0.13	−1.94 ± 0.09	3	+0.48	−2.59 ± 0.10	3	−0.26	−2.56 ± 0.08	4	+0.55
Ti I	4.98	−2.68 ± 0.03	3	+0.16	−2.24 ± 0.25	2	+0.18	−2.93 ± 0.10	2	−0.08	−2.88 ± 0.13	4	+0.22
Ti II	4.98	−2.88 ± 0.12	7	−0.04	−2.27 ± 0.21	6	+0.15	−2.83 ± 0.18	9	−0.02	−2.90 ± 0.19	12	+0.21
Cr I	5.67	−3.02 ± 0.07	2	−0.18	−3.27 ± 0.30	4	−0.85	−3.24 ± 0.21	4	−0.39	−3.38 ± 0.22	4	−0.27
Mn I	5.39	…	…	…	…	…	…	…	…	…	−4.20	syn	−1.10
Fe I	7.51	−2.82 ± 0.18	55	…	−2.40 ± 0.19	33	…	−2.86 ± 0.17	34	…	−3.15 ± 0.17	30	…
Fe II	7.51	−2.88 ± 0.20	10	…	−2.45 ± 0.22	8	…	−2.85 ± 0.11	4	…	−3.06 ± 0.15	9	…
Co I	4.91	−2.49	1	+0.35	…	…	…	…	…	…	−2.53 ± 0.15	3	+0.57
Ni I	6.25	−2.91 ± 0.08	3	−0.07	−2.25 ± 0.18	2	+0.17	−2.71 ± 0.21	4	+0.14	−2.53 ± 0.26	2	+0.30
Sr II	2.90	−3.23	1	−0.38	−3.43 ± 0.3	2	−1.01	…	…	…	−5.02 ± 0.05	2	−1.92
Y II	2.24	−3.11	1	−0.27	…	…	…	…	…	…	…	…	…
Ba II	2.13	−3.36 ± 0.20	4	−0.52	−2.80 ± 0.20	3	−0.37	−3.92 ± 0.31	4	−1.07	−4.46 ± 0.18	4	−1.35
Ce II	1.55	…	…	…	…	…	…	−2.11	1	+0.74	…	…	…

Note.—n is the number of considered lines. syn: synthetic spectrum.

Lines employed in this analysis are presented in the Table 4. The log gf values are taken from compilations provided by R. E. Luck (1992, private communication) and McWilliam et al. (1995). We derived carbon abundances for CS 22877-1, CS 22166-16, and CS 22169-35 using the CH band at 4310–4330 Å. No CH line could be detected for BS 16085−0050 in spite of its low temperature. We used hyperfine structure parameters given in McWilliam et al. for Mn I lines at 4030, 4033, and 4034 Å to synthesize this region for BS 16085−0050 to derive the Mn abundance. The same could not be done for CS 22877-1, CS 22166-16, and CS 22169-35 as Mn I lines were contaminated by CH lines. Elemental abundances are given in Table 3 as [X/H] with the standard error derived from the line-to-line scatter, the number of adopted lines, and [X/Fe]. Uncertainties arising from likely errors in the atmospheric parameters can be assessed from Ryan, Norris, & Beers (1996; Table 3 and entries for HD 122563). In almost all cases, our tabulated standard error is the dominant contributor to the total error; the standard error of the mean is formally smaller than that quoted by the square root of the number of contributing lines.

4. DISCUSSION

In the light of published results on the composition of extremely metal-poor stars, we commence our discussion by comparing and contrasting the four stars with previously analyzed stars. This will be done using the ratio [X/Fe]. Our primary reference works are the surveys by McWilliam et al. (1995) and Ryan et al. (1996) and reviews by McWilliam (1997) and Norris (1999). Variation of [X/Fe] with [Fe/H] is well determined from [Fe/H] = 0.0 to [Fe/H] ≃ −2 with remarkably little true (cosmic) scatter as long as normal stars are considered (Lambert 1989; Wheeler, Sneden, & Truran 1989). For [Fe/H] ≤ −2, many relations change shape and slope and may develop a significant cosmic scatter. Our stars will be judged as normal if they fall within the range of [X/Fe] given in the reference works. It should be noted that the analytical tools (models, lines, etc.) used here are very similar to those employed by McWilliam et al. and Ryan et al., and both samples included not only dwarfs but giants similar to our stars. Therefore, systematic errors affecting our [X/Fe] should be similar to those of the reference works. Since our principal goal is to relate our stars to the previously analyzed stars, we do not here concern ourselves with the systematic errors arising from defects in the analytical tools, e.g., the use of local thermodynamic equilibrium (LTE) when non-LTE effects may be significant.

4.1. CS 22877-1

This C-rich star at [Fe/H] = −2.8 has [X/Fe] firmly within the expected range except for Na (possibly underabundant), Al, and Ti (possibly slightly underabundant). The high C abundance is evident from the great strength of the CH bands: our estimate of [C/Fe] = +1.8 comes from a spectrum synthesis (Fig. 1). Although this star is C-rich relative to most extremely metal-poor stars, its [C/Fe] is matched by other stars (Norris, Ryan, & Beers 1997). The Na abundance, [Na/Fe] = −0.5, is a little outside the range of −0.3 to +0.4 reported by McWilliam et al., also using the Na D lines. Figure 2 shows the Al I line at 3961 Å. The Al abundance, [Al/Fe] = +0.2, is within the large range of −1.0 to +0.5 found by McWilliam et al.

TABLE 4
EQUIVALENT WIDTHS FOR THE LINES USED

Ion	Wavelength (Å)	Low EP (eV)	log *gf*	W_λ (mÅ) CS 22877-1	CS 22166-16	CS 22169-35	BS 16085−50
Na I	5889.94	0.00	0.11	112	181	128	137
	5895.94	0.00	−0.19	89	141	113	125
Mg I	4057.52	4.34	−1.00	...	...	...	26
	4167.28	4.34	−0.94	...	...	...	46
	4571.10	0.00	−5.74	22	42	...	43
	4703.00	4.34	−0.38	38	...	47	68
	5172.70	2.72	−0.38	142	212	164	202
	5183.62	2.72	−0.16	155	251	183	205
	5528.42	4.34	−0.34	36	79	46	51
Al I	3944.02	0.00	−0.63	128	...	90	113
	3961.53	0.00	−0.32	147	...	130	117
Si I	3905.53	1.91	−0.98	...	122	112	178
	4102.94	1.91	−2.72	30	50	60	99
Ca I	4302.60	1.90	−0.15	...	...	...	59
	4425.44	1.88	−0.36	31	...	...	29
	5588.76	2.52	0.36	34	60	36	34
	5594.47	2.52	0.09	...	...	...	28
	5598.49	2.52	−0.09	17	35	...	...
	6102.72	1.88	−0.80	21	...	...	...
	6122.23	1.89	−0.32	41	65	41	52
	6162.18	1.90	−0.09	48	70	64	56
	6439.08	2.52	0.39	...	83	44	49
	6493.79	2.52	−0.11	...	38	27	...
	6499.65	2.52	−0.82	...	17	...	...
Sc II	4246.84	0.31	0.02	108	122	...	123
	4320.75	0.61	−0.47	...	...	...	81
	5031.02	1.36	−0.57	...	...	...	39
	5239.82	1.45	−0.94	...	22	19	...
	5526.82	1.77	−0.22	...	...	28	34
	5657.88	1.51	−0.82	...	20	24	...
Ti I	4533.24	0.84	0.48	25	...	...	23
	4533.97	0.85	0.53	...	30	...	...
	4534.78	0.84	0.34	...	...	30	18
	4981.74	0.85	0.52	33	...	...	43
	4991.07	0.84	0.41	25	...	...	26
	4999.51	0.83	0.31	...	...	32	...
	5014.24	0.00	−1.16	...	15	...	...
	4163.66	2.59	−0.39	...	...	...	30
	4290.23	1.18	−1.12	...	...	83	89
	4337.93	1.08	−1.13	...	...	...	74
	4394.06	1.22	−1.77	...	...	...	34
	4395.04	1.56	−0.51	...	...	103	...
	4395.85	1.24	−1.96	...	...	...	27
	4417.72	1.16	−1.43	...	...	72	...
	4443.81	1.08	−0.70	...	98	...	112
	4464.46	1.16	−1.79	29	...	57	24
	4468.50	1.13	−0.59	95	...	130	95
	4501.28	1.12	−0.76	91	97	110	...
	4529.49	1.57	−1.72	15	...	...	...
	4533.97	1.24	−0.78	79	101	110	97
	4563.77	1.22	−0.78	75	112	86	89
	4571.96	1.57	−0.53	72	...	106	75
	4589.95	1.24	−1.64	39	...	...	57
	5154.08	1.57	−1.77	...	30	...	...
	5336.79	1.58	−1.65	...	34	...	...

TABLE 4
(Continued)

Ion	Wavelength (Å)	Low EP (eV)	log *gf*	W_λ (mÅ) CS 22877-1	CS 22166-16	CS 22169-35	BS 16085−50
Cr I	4254.35	0.00	−0.11	103	69	...	81
	4274.81	0.00	−0.23	...	72	...	92
	4289.73	0.00	−0.36	93	45	...	93
	4558.60	4.07	−0.66	...	...	...	11
	5206.04	0.94	0.02	...	...	61	...
	5208.43	0.94	0.16	69	69	101	...
	5345.81	1.00	−0.98	...	...	37	...
	5409.80	1.03	−0.72	22	...	38	18
Fe I	3808.73	2.56	−1.16	19	...	...	...
	3846.42	3.57	−0.43	26	...	...	...
	3878.03	0.96	−0.91	...	...	...	115
	3949.96	2.18	−1.16	53	...	...	45
	4005.25	1.56	−0.61	115	...	...	94
	4175.64	2.84	−0.67	...	...	...	21
	4199.11	3.05	0.25	83	...	...	...
	4222.22	2.22	−0.97	...	...	...	37
	4250.14	2.47	−0.40	...	...	...	68
	4260.49	2.40	−0.02	98	102	87	...
	4271.77	1.49	−0.16	...	...	...	125
	4383.56	1.48	0.20	...	...	...	138
	4388.41	3.60	−0.59	...	20	...	...
	4430.62	2.22	−1.65	33	...	...	17
	4442.35	2.20	−1.25	54	...	...	47
	4447.73	2.22	−1.34	54	...	...	...
	4459.14	2.18	−1.27	33	...	...	...
	4489.75	0.12	−3.97	...	...	75	...
	4494.57	2.20	−1.14	55	...	92	50
	4531.16	1.48	−2.17	53	53	...	43
	4678.85	3.60	−0.66	...	31	...	...
	4871.33	2.86	−0.27	58	...	...	...
	4872.14	2.88	−0.50	44	...	64	33
	4918.99	2.86	−0.34	47	...	84	47
	4920.51	2.83	0.07	68	...	...	68
	5014.95	3.94	−0.27	...	19	...	...
	5041.08	0.96	−2.89	49	...	...	35
	5049.82	2.28	−1.35	39	...	58	38
	5051.64	0.91	−2.78	55	65	93	46
	5079.23	2.20	−2.06	28	...	...	...
	5083.35	0.96	−2.91	41	...	...	39
	5123.72	1.01	−3.07	44	44	89	...
	5133.70	4.18	0.20	25	...	...	...
	5150.85	0.99	−3.00	31	...	...	...
	5151.92	1.01	−3.32	27	41	51	...
	5162.28	4.18	0.08	25	...	28	...
	5171.61	1.49	−1.76	...	71	...	...
	5194.95	1.56	−2.06	44	62	80	...
	5198.72	2.22	−2.14	...	28	...	...
	5202.35	2.18	−1.84	30	...	...	...
	5216.28	1.61	−2.12	43	50	94	...
	5232.95	2.94	−0.08	51	71	87	...
	5250.65	2.20	−2.05	...	...	33	...
	5281.80	3.04	−0.83	33	...	...	...
	5324.19	3.21	−0.10	48	...	...	...
	5328.05	0.91	−1.63	115	115	...	...
	5332.91	1.56	−2.94	...	...	30	...
	5339.94	3.26	−0.68	21	...	...	...

TABLE 4
(Continued)

Ion	Wavelength (Å)	Low EP (eV)	log *gf*	W_λ (mÅ) CS 22877-1	CS 22166-16	CS 22169-35	BS 16085−50
Fe I	5341.03	1.61	−1.95	55	…	…	…
	5371.50	0.96	−1.65	114	…	…	…
	5383.38	4.31	0.65	15	45	…	…
	5393.17	3.24	−0.72	15	47	37	…
	5405.79	0.99	−1.85	96	91	136	96
	5415.21	4.39	0.50	24	…	…	…
	5424.08	4.32	0.58	32	…	…	…
	5434.53	1.01	−2.12	91	91	127	103
	5446.92	0.99	−1.91	93	113	143	93
	5497.53	1.01	−2.84	49	65	…	46
	5501.48	0.96	−2.95	…	…	94	…
	5506.79	0.99	−2.80	50	50	102	53
	5586.77	3.37	−0.12	31	53	…	38
	5615.66	3.33	0.05	48	57	…	39
	6136.62	2.45	−1.40	27	40	67	…
	6137.70	2.59	−1.40	24	34	50	31
	6191.57	2.43	−1.42	32	46	57	…
	6213.44	2.22	−2.48	…	…	22	…
	6230.76	2.56	−1.28	…	28	…	…
	6252.57	2.40	−1.72	24	…	…	34
	6393.61	2.43	−1.43	33	33	41	43
	6400.01	3.60	−0.07	21	30	…	…
	6411.66	3.65	−0.66	13	13	…	…
	6421.36	2.28	−2.01	…	28	46	…
	6430.86	2.18	−2.01	…	33	45	…
	6678.00	2.69	−1.42	…	38	47	13
Fe II	4173.47	2.58	−2.18	72	…	…	62
	4178.87	2.58	−2.48	…	…	…	40
	4233.17	2.58	−1.91	…	73	…	60
	4385.38	2.78	−2.70	…	…	…	29
	4416.83	2.78	−2.60	37	…	…	…
	4491.40	2.85	−2.59	…	…	…	32
	4508.29	2.85	−2.31	33	…	…	32
	4515.34	2.84	−2.48	41	…	…	37
	4555.89	2.83	−2.29	…	…	54	…
	4583.84	2.81	−2.02	54	84	…	…
	4731.45	2.89	−2.92	…	22	…	…
	4923.93	2.89	−1.43	79	81	…	82
	5018.45	2.89	−1.22	98	97	111	101
	5169.03	2.89	−0.87	…	141	…	…
	5197.58	3.23	−2.25	28	30	33	…
	5234.63	3.22	−2.24	18	…	35	…
	5276.00	3.20	−1.91	24	…	…	…
	6456.39	3.90	−2.20	…	20	…	…
Co I	3995.32	0.92	−0.22	67	…	…	72
	4020.91	0.43	−2.07	…	…	…	18
	4121.33	0.92	−0.32	…	…	…	64
Ni I	3807.15	0.42	−1.18	93	…	…	…
	3858.30	0.42	−0.97	96	…	…	…
	5017.58	3.54	−0.08	…	16	…	…
	5476.92	1.83	−0.89	53	57	73	68
	6108.13	1.68	−2.45	…	…	23	…
	6643.64	1.68	−2.30	…	…	20	…
	7122.21	3.54	0.04	…	…	25	…

TABLE 4
(CONTINUED)

Ion	Wavelength (Å)	Low EP (eV)	log *gf*	W_λ (mÅ) CS 22877-1	CS 22166-16	CS 22169-35	BS 16085−50
Sr II	4077.75	0.00	0.15	...	97	...	59
	4215.54	0.00	−0.16	119	105	...	47
Y II	3950.36	0.10	−0.51	26	...	...	...
Ba II	4554.04	0.00	0.12	95	100	84	34
	4934.10	0.00	−0.15	82	90	...	20
	5853.69	0.60	−1.00	...	...	18	...
	6141.73	0.70	−0.07	30	43	18	10
	6496.90	0.60	−−0.37	18	34	23	9
Ce II	4562.37	0.48	0.32	...	...	40	...

NOTE.—EP: Excitation potential.

from the 3961 Å Al I resonance line; the other resonance line at 3944 Å was shown by Arpigny & Magain (1983) to be blended with several CH lines, even in stars where CH was not the prominent feature of the spectrum that it is for CS 22877-1. Ryan et al.'s analyses of the resonance line, however, gave a rather well-defined "plateau" at [Al/Fe] $\simeq -0.8$; relative to this value (and to points in their [Al/Mg] vs. [Fe/H] plot), CS 22877-1 is Al-enriched, but analysis of the 3961 Å line is sensitive to the adopted microturbulence. The origin of the difference between the Al abundances of McWilliam et al. and Ryan et al. is unclear, according to Ryan et al. Clearly, there is a need to probe this discrepancy more deeply because classification of Al abundances for the four stars as "normal" or "abnormal" depends on whether the appropriate set of reference abundances is that offered by McWilliam et al. or that by Ryan et al. We do not attempt to resolve the discrepancy. In Figure 3, we show the star's location in [X/Fe] versus [Fe/H] plots for X = Al, α, where α denotes Mg and Ca. Abundances from McWilliam et al. and Ryan et al. are given as a reference. We chose not to include [Si/Fe] as not many good Si I lines were accessible. The abundances of the three measured elements from Sr to Ba are each within the ranges defined by McWilliam et al. and Ryan et al.

4.2. CS 22166-16

CS 22166-16 at [Fe/H] $= -2.4$ is enriched in carbon relative to the typical value [C/Fe] $\simeq 0$, but to a more moderate and seemingly more common level than CS 22877-1. Other elements are at or close to their expected levels. Mg and Ca abundances are well determined and provide [α/Fe] $= 0.6$. The Si abundance based on a single weak line is [Si/Fe] = 0.2. Chromium is underabundant at [Cr/Fe] $= -0.9$; McWilliam et al. and Ryan et al. find [Cr/Fe] $\simeq -0.2$ for [Fe/H] $= -2.4$ with a few outliers at lower [Cr/Fe]. Na has a normal abundance according to McWilliam et al.'s results. The abundances of Sr and Ba, the only measured heavy elements, fall within the cosmic scatter previously reported with [Sr/Fe] at the lower boundary of previous results.

4.3. CS 22169-35

Relative to the expected composition of a [Fe/H] $= -2.9$ star, a striking aspect of CS 22169-35 is the low abundance of the α-elements Mg, Si, Ca, and Ti. Magnesium and calcium, which are well represented, give [Mg/Fe] = 0.0 and [Ca/Fe] = 0.1. Titanium from nine Ti II lines gives [Ti/Fe] = 0.0 (Fig. 3), a result consistent with that from the two Ti I lines. The mean index [α/Fe] from Mg and Ca (Fig. 3) is smaller than any index measured by McWilliam et al. and Ryan et al. McWilliam et al. found three stars with a [Mg/Fe] well below the expected values, and one of these stars was also low in Ca, the only low Ca star in their sample. Carbon is slightly enriched: [C/Fe] $\simeq +0.4$, where [C/Fe] $\simeq 0.0$ is accepted as normal. Aluminum at [Al/Fe] $= -0.7$ is not exceptional and belongs to Ryan et al.'s plateau. Sodium from the Na D lines appears distinctly underabundant relative to McWilliam et al.'s sample at [Na/Fe] = -0.7.

A metal-poor star with low α-element abundances is unusual although not unprecedented. Our star is reminiscent of the pair HD 134439/134440 (King 1997; James 2000) at [Fe/H] = -1.5. These common proper motion stars have a higher Ba abundance ([Ba/Fe] $\simeq -0.2$ vs. -1.1), but this may reflect the metallicity difference of 1.4 dex. At a metallicity closer to that of CS 22169-35, BD +80°245 (Carney et al. 1997; James 2000) with [Fe/H] $= -2.0$ has low abundances of the α-elements (Mg, Ca, and Ti at [α/Fe] $\simeq -0.2$) and Ba ([Ba/Fe] $= -1.3$). James also found low Mg and Ca (and Ba) but not Ti abundances in the star G4-36 with [Fe/H] $= -2.0$. A group of α-poor stars with [Fe/H] $= -1.2$ to -0.6 was uncovered by Nissen & Schuster (1997), who delineated several abundance trends. Their correlation between [Na/Mg] and [Mg/H] does not extend to lower [Fe/H], but our results, and also the results by James (2000), suggest an approximately constant [Na/Mg] at low [Fe/H]. On

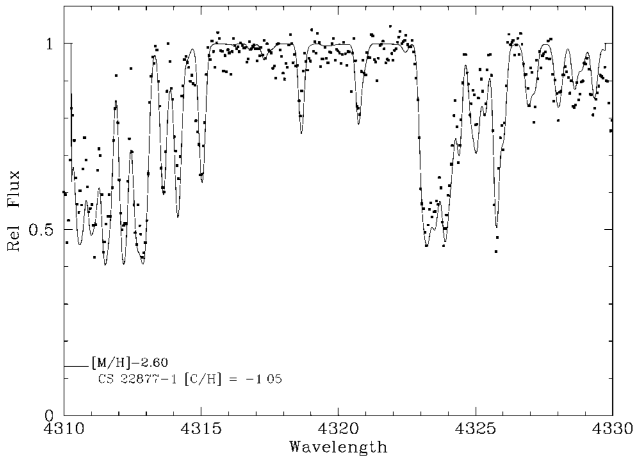

FIG. 1.—Observed and synthetic spectra of CS 22877-1 at high resolution showing CH lines. The synthetic spectrum is computed for [C/Fe] $= +1.8$.

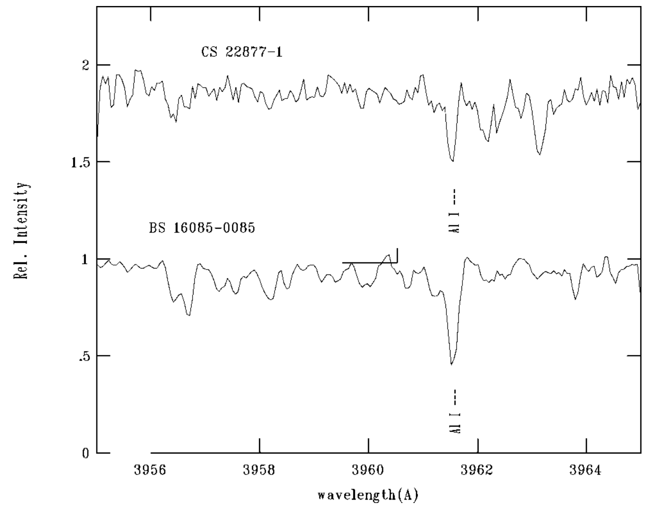

FIG. 2.—Observed spectra of CS 22877-1 and BS 16085−0050 showing the Al I line at 3961 Å.

the other hand, the [Ni/Fe] versus [Fe/H] trend suggested by Nissen & Schuster is not satisfied by α-poor low [Fe/H] stars.

4.4. BS 16085−0050

The outstanding aspect of this star's composition, the most iron-deficient of the quartet at [Fe/H] $= -3.1$, is the high abundance of the α-elements. With [α/Fe] $= 0.9$, 1.2, and 0.6 for Mg, Si, and Ca, respectively, it is unmatched by any of Ryan et al.'s stars. McWilliam et al. found one star with similarly high [α/Fe] values: CS 22949-037 with [α/Fe] $= +1.2$, 0.9, and 0.9 for Mg, Si, and Ca, respectively, and [Fe/H] $= -4.0$. Titanium, sometimes grouped with the α-elements, is a little below its expected abundance at [Ti/Fe] $= 0.2$. In CS 22949-037, Ti is only marginally above its expected value.

BS 16085−0050's high abundance of α-elements is a robust result. A high [α/Fe] is clearly indicated for Mg and Ca. Magnesium is represented by seven Mg I lines, including two strong lines and five weaker lines. Seven medium-strong Ca I lines give consistent results. If the atmospheric parameters are varied by their estimated uncertainties, [Mg/Fe] and [Ca/Fe] do not vary by more than about ± 0.05. No plausible change can reduce the best estimates [Mg/Fe] $= 0.9$ and [Ca/Fe] $= 0.6$ to the lower, more typical values. Silicon is represented by just two lines. Variation of the atmospheric parameters has a larger effect on the [Si/Fe] ratio in part because the Si I lines are sensitive to the adopted microturbulence, but the effect is much smaller than the difference between the estimated [Si/Fe] $= 1.2$ and the lower value from the published surveys. Titanium, for which adequate samples of Ti I and Ti II lines provide consistent results, clearly gives a lower ratio of [Ti/Fe] $= 0.2$, with very little sensitivity to the atmospheric parameters. In summary, Mg and Ca and most likely Si but not Ti are unusually enriched in this star. Magnesium and calcium are well represented in all stars, and therefore the star-to-star differences in [α/Fe] are considered real.

Aluminum is approximately normal judged by McWilliam et al.'s range in [Al/Fe] and by Ryan et al.'s [Al/Mg], but not their [Al/Fe] range where BS 16085−0050 appears overabundant in Al. Heavy elements Sr, Y, and Ba fall just within the previously reported spreads for stars with [Fe/H] ~ -3. Their [X/Fe] values are at the lower boundaries of previous results.

5. CONCLUDING REMARKS

A somewhat surprising outcome of our initial survey of Lee's high-velocity stars is the absence of metal-poor stars. Most stars appear to have an abundance near solar. Given that the selection criterion was a tangential velocity in excess of 100 km s^{-1}, we expected to find a rather metal-poor sample. This apparent puzzle will be considered when our survey is more complete.

Our modest addition to the number of very metal-poor stars subjected to an abundance analysis reveals several interesting facets about these stars. Two of the stars are evidently very rich in carbon. This is not an uncommon feature of very metal-poor stars (Rossi, Beers, & Sneden 1999). At solar metallicities, carbon enrichment of a stellar atmosphere is widely associated with enrichment of *s*-process elements and attributed to contamination of the star by mass transfer from an asymptotic giant branch star. This attribution is far less appropriate for very metal-poor stars. Several C-enriched stars have been shown not to be binaries (Norris et al. 1997), and in addition the C enrichment is not always coupled with *s*-process enrichment. In short, mass transfer is a plausible explanation in only some cases, and in others the C enrichment was likely present in the star's natal cloud. In the case of CS 22877-1 and probably also CS 22877-16, the carbon enrichment is not related to the *s*-process, but heavy elements point to an *r*-process connection. Whether these stars are binaries or not is presently unknown.

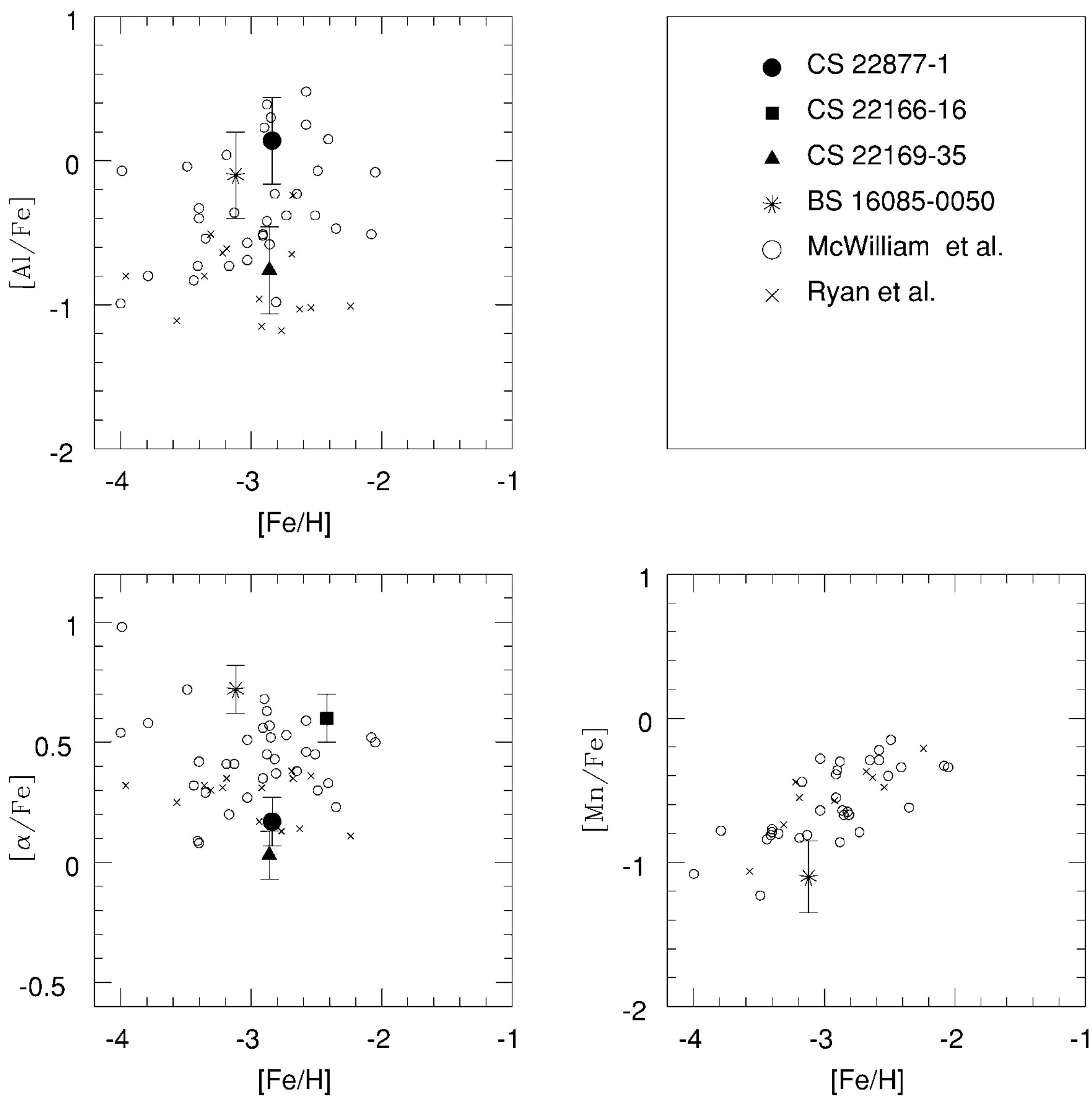

FIG. 3.—[X/Fe] vs. [Fe/H] for X = Al, α, and Mn, where [α/Fe] is the mean of [Mg/Fe] and [Ca/Fe]. Abundances from McWilliam et al. and Ryan et al. are given as a reference.

Very metal-poor stars are apparently not a monolithic block with respect to the ratio of α-elements to iron. BS 16085−0050 is α-enriched at a level rarely seen previously, but this enrichment is not unprecedented: CS 22949-37 is similar (McWilliam et al. 1995). At the other extreme, CS 22169-35 joins a small group of α-poor very metal-poor stars. Star-to-star spread in elemental abundance ratios with respect to iron are seen in some other elements, particularly the heavy elements, where a considerable dispersion has been noted previously.

The large spread in abundances particularly for α-elements found for stars with [Fe/H] < -2.5 indicates that before this metallicity level was attained, the early Galaxy experienced very unusual chemical enrichment. Refinement of supernovae models are perhaps required to explain the uneven yield of α-elements. Galactic chemical enrichment models including the effect of incomplete mixing might help in explaining the observed abundance peculiarities. Perhaps the principal lesson to be drawn from our small sample is that not everything has yet been gleaned from abundance analyses of very metal-poor stars. The mine is not yet exhausted of valuable ores.

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