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A High Resolution Spectroscopic Study of Eight Metal-Poor Stars

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We present the results of a high resolution spectroscopic study of eight metal-poor stars previously identified by low resolution Ca II K line surveys as having [Fe/H] ≤ -3.00. An abundance analysis code (WIDTH6) utilising one dimensional model atmospheres (MARCS) is used to constrain the stellar parameters (surface gravity, effective temperature, and microturbulence) and to obtain local thermodynamic equilibrium (LTE) abundances for seventeen atomic species. We note the following basic results: (1) The general trend for [α/Fe] to plateau at approximately 0.40 dex, as noted in earlier investigations, is observed for our sample with several exceptions. (2) BS 16479–035 appears to be alpha-poor for Mg, Ti, and Ca. (3) CS 30336–049 and BS 16550–087 exhibit enhanced Mg abundances. (4) BS 16550–087 shows a significant enhancement in [Al/Fe], [Sr/Fe], and [Y/Fe] with a high [Sr/Ba] value.

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1. Introduction & Observations

Metals (all elements with an atomic mass heavier than He) are formed predominantly in evolving stars by various nucleosynthetic processes. High mass stars which formed in the early Universe evolved quickly, enriching the pristine interstellar medium (ISM) at the end-point of their lives. Further stars evolved from the enriched ISM. Low-mass stars which formed during this time can still be observed in the Galaxy and have [Fe/H] ≤ -3.00, an iron abundance one thousand times less than that of the Sun. Study of these objects allows us greater understanding of the chemical history of the Galaxy, and places constraints on the metallic yields from the first supernovae.

Eight metal-poor stars previously identified as having [Fe/H] ≤ -3.00 from Ca II K line surveys following on from Beers et al. [4] were selected for a high resolution spectroscopic study. The objects chosen are listed in Table 1. In addition, the previously studied metal-poor standard CS 22968–014 was observed to check the robustness of our reduction and analysis procedures.

High resolution spectra were obtained for all eight objects using the University College London coudé échelle spectrograph (UCLES) on the 3.9 m Anglo-Australian Telescope. Observations were performed over five nights during July 2001 using the EEV2 CCD detector. All of the spectra have a high resolving power ($R = 34,000$), with a high signal-to-noise ratio (typically 40 per 0.026 Å pixel at 4300 Å, obtained by co-adding several spectra), covering the wavelength region 3750 Å to 4850 Å. Figure 1 shows examples of flux-normalised spectra for two objects in the wavelength region 4060 Å to 4080 Å. As the objects in Figure 1 have similar atmospheric parameters, it is possible to make a comparison between the two; it is clear that the Sr abundance (as indicated by the line at 4077.71 Å) is different for each object.

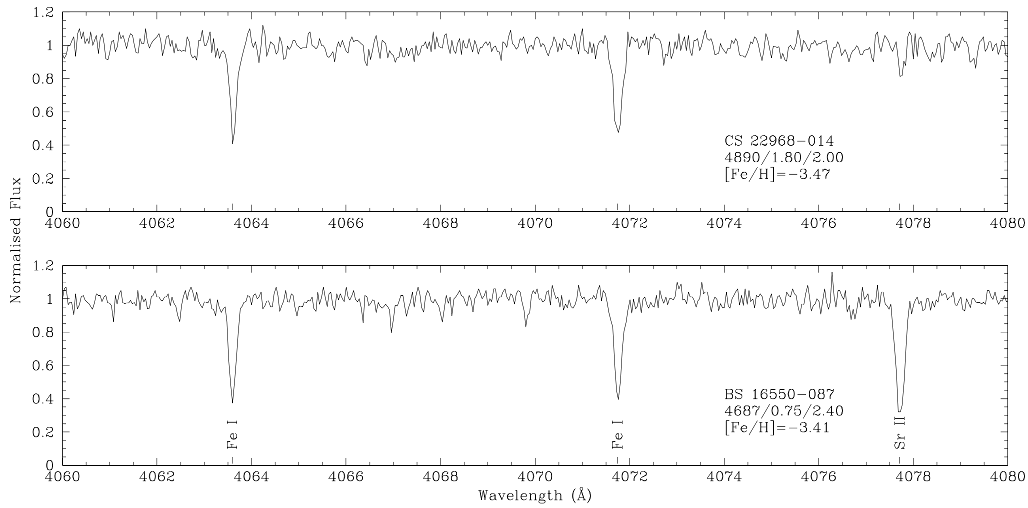

Figure 1: Sample spectra covering the wavelength region 4060 Å to 4080 Å for the metal-poor standard CS 22968–014 (*top panel*) and the giant BS 16550–087 (*bottom panel*). The atmospheric parameters $T_{\rm eff}$, $\log g$, ξ, and [Fe/H] are shown.

Star	$B-V$	$E(B-V)$	$T_{\rm eff}$ (K)	$\log g$	[Fe/H]	ξ (km s^{-1})	[Mg/Fe]	[Sr/Fe]
CS 22968–014	0.72	0.00	4890	1.80	–3.47	2.00	0.46	–1.83
BS 16479–035	0.87	0.00	4633	1.10	–2.84	2.40	–0.17	–0.66
CS 30306–132	0.74	0.01	5002	2.00	–2.71	1.90	0.49	0.00
CS 31081–049	0.90	0.00	4557	0.65	–3.02	3.20	0.43	–0.63
CS 22950–046	0.91	0.06	4587	1.25	–3.53	2.00	0.34	–0.39
CS 30336–049	0.90	0.08	4876	1.60	–3.75	1.80	0.75	–1.74
BS 16550–087	0.83	0.00	4687	0.75	–3.41	2.40	0.97	0.23
CS 30302–145	0.38	0.05	6430	4.20	–2.96	1.40	<0.97	<–1.01

Table 1: Colours, basic atmospheric parameters, and selected abundances for the program stars. The solar abundance values of Anders & Grevesse [1] were used to make a direct comparison with previous work.

2. Reduction & Analysis

The spectra were reduced using the IRAF package `echelle`. Equivalent width (EW) measurements for seventeen atomic species were made. Kurucz's WIDTH6 program [10] was used to calculate LTE abundances for each of the lines. Various atomic data and initial estimates of the effective temperature ($T_{\rm eff}$), surface gravity ($\log g$), and metallicity (defined as [Fe/H]) were required for each star. We adopted the new MARCS model atmosphere grid [9]. The abundance was determined for each line by adjusting the abundance estimate until the calculated EW matched that observed.

Kron-Cousins photometry ($B-V$, $V-R$, $V-I$, and $R-I$) was available for all eight objects (T. C. Beers 2005 - private communication) and was used to derive estimates for $T_{\rm eff}$. These data were de-reddened using the reddening maps of Burstein & Heiles [7]. We adopted the photometric calibrations of Magain [11] (for the dwarf CS 30302–145) and Bell & Gustafsson [5, 6] (for the remaining giants). Log g was determined using the requirement that the derived Fe I and Fe II abundances should be identical. When there were two or fewer Fe II lines measured in a star, a $\log g$ derived from the theoretical isochrones of Demarque et al. [8] was adopted. The microturbulent velocities, ξ, were found by removing any apparent trend between abundance and equivalent width. A summary of the final atmospheric parameters, along with the derived [Fe/H] value for each star is presented in Table 1.

3. Results & Discussion

Of the eight stars in the study, we find five with [Fe/H] < -3.00, two of these having [Fe/H] < -3.50. Uncertainties (2σ) were calculated by adjusting $T_{\rm eff}$ by +100 K, $\log g$ by +0.2 dex, and ξ by +0.2 km s^{-1}; we obtain σ[Fe/H] values of 0.06 dex at the main sequence turn-off, and 0.05 dex on the giant branch. Hyperfine splitting corrections were applied to Mn I, Co I, Ba II, and Eu II. CS 22968–014 was previously studied by Ryan et al. [13] who determined [Fe/H] $= -3.43$, $\log g = 1.80$, and $\xi = 2.30$ km s^{-1} using a photometrically determined $T_{\rm eff}$ of 4950 K. Our analysis of this star is in good agreement.

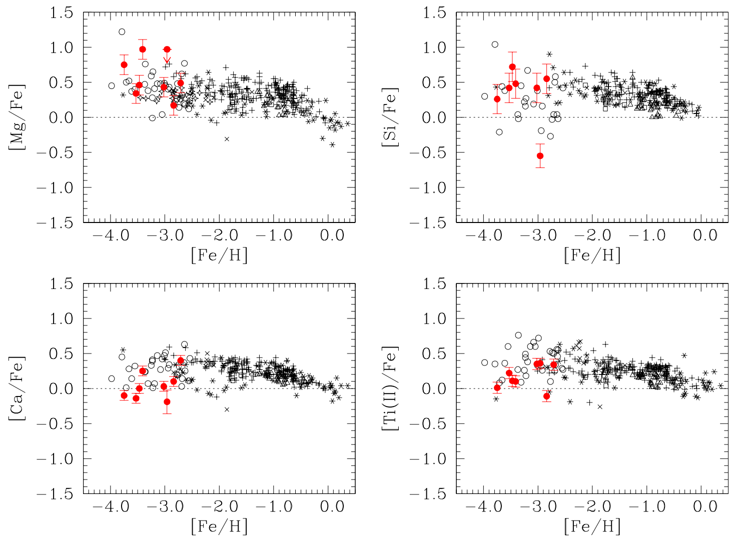

Figure 2: [α/Fe] vs. [Fe/H]. Our data (*red filled circles*) plotted against data from the literature (after Figure 5 of Norris et al. [12] - data and symbols).

Figure 2 presents the results of this study, in combination with data taken from the literature, for the α-elements Ti II, Mg I, Ca I, and Si I. The general trend for [α/Fe] to plateau at approximately 0.40 dex for [Fe/H] < -1.00, as noted in previous investigations, is again observed for our stars with several notable exceptions. BS 16479–035 appears to be α-poor as [Ti/Fe], [Mg/Fe], and [Ca/Fe] are all low (–0.11, 0.17, and 0.10 respectively). [Si/Fe] does not exhibit this behaviour (with a value of 0.55 it is normal) but our measurement is based upon only a single line (3905 Å); until this determination has been verified this value should be treated with caution. Both CS 30336–049 and BS 16550–087 show an enhanced [Mg/Fe] (0.75 and 0.97 respectively) without any significant enhancement in the remaining α-elements.

BS 16550–087 also shows a significant enhancement in [Al/Fe], [Sr/Fe], and [Y/Fe] (0.02, 0.23, and 0.45 respectively) with a high [Sr/Ba] value (1.38). Aoki et al. [2, 3] have previously studied three metal-poor stars which show an enhanced [Mg/Fe] value. Although Aoki et al. did not remark upon high [Sr/Fe] and [Y/Fe] being linked to the high abundances observed for the light elements Mg and Al, their results for CS 22949–037 and CS 29498–043 show a similar enhancement pattern to that of BS 16550–087 (Figure 3); their third star, BS 16934–002, has a lower [Sr/Fe] and [Y/Fe]. All three stars studied by Aoki et al. showed enhanced [C/Fe] and [N/Fe]; we have yet to compute these abundances for our stars and therefore cannot comment on the abundance trend of BS 16550–087 for Z < 12.

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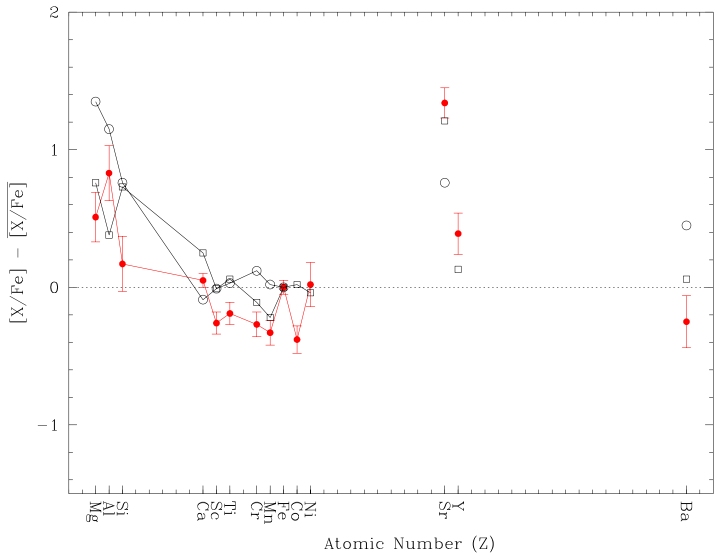

Figure 3: Abundances relative to the mean of the four stars studied by Norris et al. [12] excluding CS 22949–037. BS 16550–087 is presented with *red filled circles*, whilst CS 29498–043 and CS 22949–037 (Aoki et al. [2]) have *open circles* and *open squares* respectively.

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