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ASTRONOMY AND ASTROPHYSICS

The chemical composition of the extreme halo stars

II. Green spectra of 20 dwarfs*

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Abstract. The abundances of 9 elements in the atmospheres of 20 extreme metal-poor stars are derived from green spectra obtained with the ESO Cassegrain Echelle Spectrograph (CASPEC). For the elements in common with our previous analysis of blue CASPEC spectra, the agreement is generally very good.

The main results are:

(1) Sodium is overabundant with respect to aluminium, by as much as one dex.

(2) There is some scatter in [Ca/Fe] which cannot be accounted for by random errors in equivalent widths or atmospheric parameters.

(3) Scandium is overabundant relative to iron.

(4) Some barium lines may be affected by strong departures from local thermodynamic equilibrium.

(5) The nitrogen-rich metal-poor star HD 74000, which was found in our previous work to be also Al-rich, presents as well higher than usual abundances of Na and of *s*-process elements. It can thus be considered as a mild barium dwarf of Population II. This case suggests a related origin for the nitrogen and heavy elements enhancements.

Key words: stellar abundances – population II stars – chemical evolution of the Galaxy – non-LTE effects

1. Introduction

In the first paper of this series (Magain, 1989 = Paper I), the abundances of 13 elements in the atmospheres of 20 extremely metal-poor stars were determined from the analysis of spectra covering the range 3700–4700 Å. Some of the consequences of these results for the models of nucleosynthesis and galactic evolution were also briefly discussed.

The present paper deals with the analysis of a second series of spectra, covering the range 5000–6000 Å, which were obtained for the same sample of 20 stars. New abundance results are presented for two elements, sodium and nickel, which had no line of suitable strength in the blue spectra previously analysed. For two other elements, scandium and barium, the present spectra contain lines which should be better suited for an accurate abundance determination and, thus, allow to significantly refine the results. Abundances are also obtained for five other elements in common with Paper I (calcium, titanium, chromium, iron and yttrium) and allow in most cases to improve and better assess the accuracy of our results.

2. Data acquisition and analysis

The spectra were obtained with the Cassegrain Echelle Spectrograph (CASPEC) attached to the 3.6 m telescope at the European Southern Observatory (La Silla, Chile). The detector was a RCA CCD (type 501 EX, 320 × 512 pixels of 30 μm² each). The 32 grooves/mm Echelle grating was used along with the 300 grooves/mm cross-disperser and a 1.″5 slit, leading to a resolving power of the order of 20000. The integration time was chosen in order to obtain a signal-to-noise ratio of at least 100 over the entire spectral range. The journal of the observations is summarized in Table 1.

The spectra were reduced with the MIDAS package on a VAX 8600 computer at ESO, Garching. The first reduction steps consisted in locating the (∼20) Echelle orders on the CCD frame, subtracting the background light (approximated by a two-dimensional low order polynomial) and extracting the orders by summation along the slit. The pixel-to-pixel sensitivity variations were found to be negligible on that particular CCD chip (ESO nr. 3) in the wavelength range considered. No flat-field correction was thus applied. The wavelength calibration was based on thorium lamp spectra obtained immediately before or after the stellar spectra.

The continuum level was determined in a number of windows (typically 20 to 30 per order) selected by inspection of the solar atlases. The shape of the continuum was represented by a semi-empirical function of the form

$$I = AX^{-2}\sin^2 X + B\sin X + C$$

with

$$X = \alpha m(1 - \lambda_0/\lambda),$$

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* Based on observations collected at the European Southern Observatory, La Silla, Chile

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Table 1. Journal of the observations

Star	V	Obs. date	Exp. (min)
HD 3567	9.25	14/15 Oct 86	16
HD 16031	9.78	14/15 Oct 86	20
HD 19445	8.05	14/15 Oct 86	7
HD 34328	9.43	14/15 Oct 86	16
HD 59392	9.72	10/11 May 86	25
HD 74000	9.64	10/11 May 86	18
HD 84937	8.30	10/11 May 86	5
HD 116064	8.80	10/11 May 86	9
HD 122196	8.74	10/11 May 86	12
HD 140283	7.21	10/11 May 86	5
HD 160617	8.74	10/11 May 86	17
HD 166913	8.23	10/11 May 86	5
HD 181743	9.69	14/15 Oct 86	30
HD 194598	8.35	14/15 Oct 86	7
HD 213657	9.67	10/11 May 86	23
BD–10°0388	10.37	14/15 Oct 86	40
BD+02°3375	9.95	10/11 May 86	30
BD+03°0740	9.81	14/15 Oct 86	28
BD+17°4708	9.47	14/15 Oct 86	20
CD–33°3337	9.08	14/15 Oct 86	13

where λ is the wavelength, m is the order number, $\alpha\,(\sim 0.8)$, λ_0, A, B, and C are adjustable parameters, determined by non-linear least squares fitting through the continuum windows. Division of the original spectrum by the fitted curve yielded the normalized spectrum.

The equivalent widths were determined with the help of the IHAP package running on a HP 1000 computer at ESO, Garching. Two different methods were used: (1) direct integration of the line profile and (2) gaussian fitting, the latter being preferable in the case of faint lines, but unsuitable for the strong lines in which the damping wings contribute significantly to the equivalent width. The final equivalent widths are weighted averages of these two measurements. These equivalent widths, along with the ones measured on the blue spectra, will be published in a subsequent paper.

The method of analysis is identical to that of Paper I, the same models being used, with the same atmospheric parameters. The reader is thus referred to Paper I for more details as well as for a discussion of the expected uncertainties. Let us just recall that, as usual, we assume local thermodynamic equilibrium (LTE) to be valid. Instead of a differential analysis relative to the sun, we prefer, as usual, to adopt an absolute method – based on laboratory oscillator strengths – for reasons discussed in Magain (1985) and in Paper I. These oscillator strengths, unless explicitely stated, come from the same sources as in Paper I.

3. Results and discussion

The derived abundances are summarized in Table 2. The main results will be discussed in this section, along with some of their consequences for stellar abundance determinations and for the chemical evolution of the Galaxy.

Table 2. Element abundances

Star	[Fe/H]	[Na/Fe]	[Ca/Fe]	[Sc/Fe]	[Ti/Fe]	[Cr/Fe]	[Ni/Fe]	[Y/Fe]	[Ba/Fe]	$[Ba/Fe]_{blue}$
HD 3567	–1.43	+0.34	+0.30	+0.25	+0.14	–0.01	+0.01	+0.06	+0.01	+0.30
HD 16031	–1.95	+0.57	+0.41	+0.28	+0.33	–0.02	+0.17	+0.06	–0.20	+0.12
HD 19445	–2.24	+0.32	+0.42	+0.39	+0.33	+0.01	+0.11	—	—	–0.10
HD 34328	–1.86	+0.15	+0.35	+0.26	+0.40	–0.02	+0.15	+0.16	+0.25	+0.08
HD 59392	–1.84	+0.47	+0.45	+0.40	+0.47	+0.02	+0.06	+0.17	+0.22	+0.46
HD 74000	–2.22	+0.87	+0.45	+0.38	+0.17	+0.11	+0.16	+0.40	+0.35	+0.15
HD 84937	–2.36	+0.28	+0.46	+0.31	+0.39	+0.08	—	–0.03	—	–0.10
HD 116064	–2.15	+0.60	+0.46	+0.24	+0.43	+0.10	+0.13	–0.05	—	+0.13
HD 122196	–2.05	+0.72	+0.40	+0.12	+0.22	+0.03	+0.22	–0.14	–0.22	+0.13
HD 140283	–2.73	+0.15	+0.27	+0.14	+0.60	–0.20	—	–0.59	—	–1.13
HD 160617	–2.01	+0.84	+0.39	+0.28	+0.22	–0.04	+0.08	+0.09	+0.16	+0.47
HD 166913	–1.75	+0.43	+0.42	+0.36	+0.31	–0.01	+0.17	+0.22	+0.17	+0.30
HD 181743	–2.05	+0.22	+0.32	+0.27	+0.27	+0.04	+0.15	—	+0.24	–0.04
HD 194598	–1.38	+0.23	+0.28	+0.17	+0.13	+0.03	+0.05	–0.01	+0.19	–0.07
HD 213657	–2.14	+0.60	+0.44	+0.30	+0.44	+0.02	—	–0.07	—	+0.14
BD –10°0388	–2.63	+0.23	+0.53	+0.46	—	+0.06	—	—	—	–0.25
BD+02°3375	–2.56	+0.30	+0.46	+0.04	+0.47	–0.12	—	–0.07	—	–0.40
BD+03°0740	–3.00	–0.22	+0.44	—	—	—	—	—	—	–0.85
BD+17°4708	–1.89	+0.70	+0.54	+0.27	+0.41	+0.11	+0.07	–0.03	–0.08	+0.24
CD –33°3337	–1.61	+0.61	+0.34	+0.28	+0.27	–0.03	+0.18	+0.07	+0.16	+0.26

Note: The barium abundances listed in Table 4 of Paper I were computed with an approximate correction for hyperfine structure, contrary to the values plotted in Fig. 14 of that paper, for which hfs was taken properly into account. These more correct values are listed here under the label $[Ba/Fe]_{blue}$.

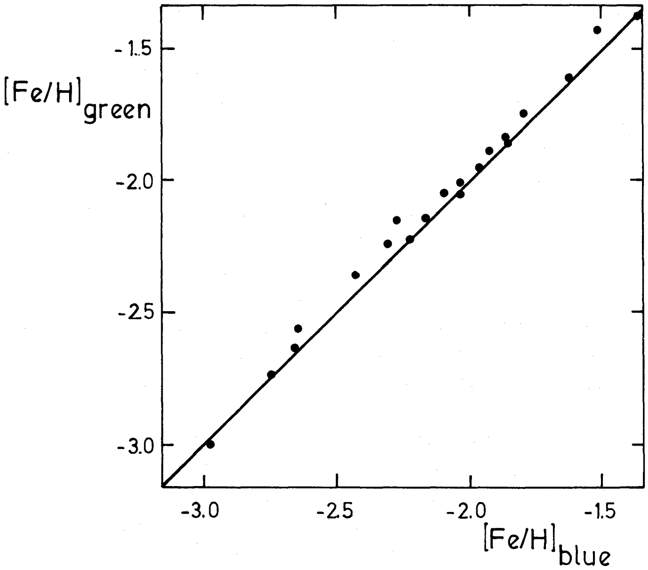

Fig. 1. Comparison of the [Fe/H] values found in the present work (green spectra) with the determinations of Paper I (blue spectra)

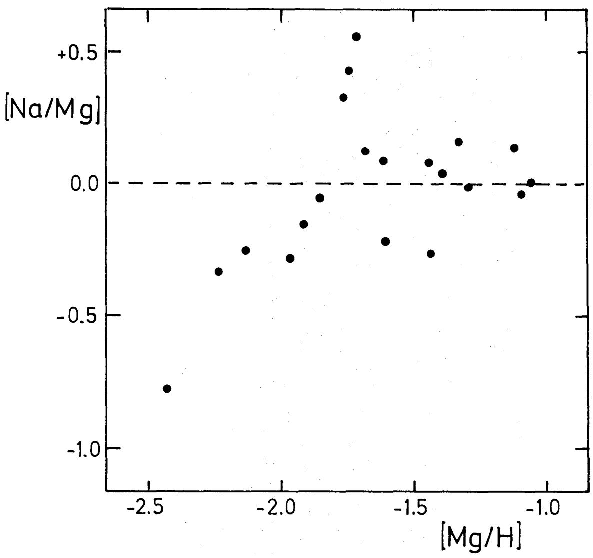

Fig. 2. [Na/Mg] versus [Mg/H]. Magnesium abundances are taken from Paper I

3.1. Iron

As usual, iron, which is the element having the largest number of measurable lines, will be taken as the reference element. The iron abundances, as determined from Fe I lines measured on the green spectra, are compared with the results of Paper I in Fig. 1. The agreement is very good, the mean difference (this paper minus Paper I) amounting to 0.04 dex, with a scatter of 0.04 dex (standard deviation of the individual values).

3.2. Sodium

The sodium abundance is determined from the D lines, with oscillator strengths from Wiese and Martin (1980) and a damping constant γ_6 equal to 1.2 times the Unsöld value (i.e. a damping enhancement factor $f_6 = 1.2$). The solar abundance is taken from Lambert and Luck (1978): $\log A_{\mathrm{Na}} = 6.32$. Although the D lines lie on the flat (or damping) part of the curve of growth in most stars of this sample (and are thus far from optimal for abundance determinations), they have to be used since other Na lines are too faint to be measured on CASPEC spectra.

An additional uncertainty comes from the numerous telluric water vapor lines which are present in that spectral region. This point has been discussed in detail by Gratton and Sneden (1988) who concluded that it should not introduce errors of more than 5 mÅ on the D lines equivalent widths.

Finally, the interstellar D lines may also contribute to the measured equivalent widths and thus introduce systematic overestimates of the stellar Na abundance in some stars, especially the faintest – and thus most distant ones – if they have low radial velocities (the interstellar lines should be well separated from the stellar lines in high radial velocity stars). In particular, the radial velocities of HD 16031, HD 84937 and HD 122196 are too low to guarantee that interstellar lines do not contribute to the measured equivalent widths. Sodium abundances for these stars should therefore be considered as upper limits.

The results are plotted in Fig. 2 from which the following conclusions may be drawn.

(1) The odd-even effect in Na–Mg is enhanced only for stars with $[\mathrm{Mg/H}] \lesssim -1.8$, that is $[\mathrm{Fe/H}] \lesssim -2.3$. This is in contrast with the results for the Al–Mg pair (Paper I) where Al already starts to become overdeficient relative to Mg at $[\mathrm{Fe/H}] \sim -1$. Na and Al thus seem to behave in very different ways, in contradiction with the predictions of explosive carbon burning theories (see, e.g., Arnett, 1971). For our sample of extreme halo stars, we get

$$[\mathrm{Na/Al}] \simeq +1.0\,(\pm 0.3).$$

Although the strength of the Na and Al resonance lines makes them rather ill-suited for an accurate abundance determination, the difference is too large to be explained by uncertainties in equivalent widths and atmospheric parameters. In this respect, it is interesting to consider the case of BD + 3°740, the most metal-poor star in our sample, in which these lines are so weak (35 to 60 mÅ) that they become good abundance indicators, and for which we obtain $[\mathrm{Na/Al}] = +0.6$.

(2) Three stars, namely HD 74000, HD 122196 and HD 160617, stand above the mean trend. As noted earlier, HD 122196 has a relatively low radial velocity and interstellar lines may contribute to the equivalent widths. The other stars are "nitrogen-rich metal-poor stars", which also display strong Al lines (Paper I). The present results thus confirm the relative overabundance of the odd elements Na and Al in such stars.

Our results are in reasonable agreement with those of Gratton and Sneden (1988) for giants, although the slope in the [Na/Mg]–[Mg/H] relation is less obvious in their data. However, that study was also based on the D lines. The comparison with recent determinations based on excited lines is less satisfactory, the latter indicating lower Na abundances (François, 1986; Gratton and Sneden, 1987 – see also Lambert, 1989 for a discussion). Such a discrepancy might be due to departures from LTE in either the resonance or the excited lines (or both). Note, however, that it goes in the direction opposite to the effect found for Al (the Al I resonance line possibly indicating lower abundances than the excited lines).

Finally, it may be interesting to point out that, at the metallicity at which Na starts to become overdeficient with respect to Mg ([Fe/H] ~ −2.3), it was also found in Paper I that the behaviour of several other abundance ratios changed (e.g., [Ba/Fe] starts to become negative, [Al/Mg] flattens, ...). These changes of behaviour suggest that something (?) might have happened when the metallicity of the halo gas reached that value (onset of some nucleosynthetic process?, ...).

3.3. Calcium

As already found in Paper I, calcium is clearly overabundant relative to iron:

$[Ca/Fe] = +0.41 \pm 0.08.$

The present value is in rather good agreement with the one deduced from the blue spectra ($+0.47 \pm 0.08$). Again, the scatter is very small. Despite the smallness of this scatter, however, we have two independent indications that part of it cannot be accounted for by random errors in the measured equivalent widths, but might be real.

The first indication comes from the comparison of the Ca, Ti, and Fe abundances. While the scatter in [Ca/Fe] and [Ti/Fe] is of the order of 0.08–0.09 dex, the scatter in [Ca/Ti] amounts to 0.05 dex only. Since the Ca and especially the Ti lines are much less numerous than the Fe lines, and since the effect of model uncertainties on these three abundance ratios is similar, there might be a real (cosmic) scatter in Fe relative to Ca and Ti.

The second (and strongest) indication is illustrated in Fig. 3 which shows that there is a clear correlation between the values of [Ca/Fe] deduced from the green and blue spectra. This correlation would not be present if the scatter in [Ca/Fe] was dominated by random errors. The mean difference ("green" minus "blue") amounts to −0.06 dex, with a scatter of 0.05 dex. This scatter is significantly smaller than the value of $\sqrt{2} \times 0.08 = 0.11$ which would be expected from random errors. Moreover, as the scatter in [Ca/Fe] due to the expected uncertainties in the stellar atmospheric parameters is of the order of 0.02 dex only (e.g., an error of 0.08 dex in [Ca/Fe] would require an error of more than 300 K in effective temperature, see Table 3 of Paper I), the source of this additional scatter has to be found somewhere else. It might be real but might also be due to errors in the analysis (departures from LTE?). The present data do not allow to decide between these two interpretations.

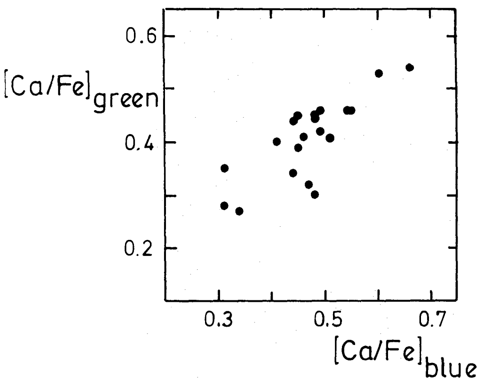

Fig. 3. Comparison of [Ca/Fe] as deduced from the blue and green spectra

3.4. Scandium

Two weak Sc II lines are measurable on the present spectra, while two stronger lines were used in Paper I. Our previous analysis did not consider the effect of hyperfine structure and used a relatively low solar Sc abundance. As discussed by Lambert (1989), this could partly explain why our values disagree with those of other investigators (e.g. Gratton and Sneden, 1988) who, by the way, did not consider hyperfine structure either. Moreover, the oscillator strengths available at that time were of rather poor quality. Since better values have been determined in the meantime (Lawler and Dakin, 1989), we decided to reanalyse the four Sc II lines together.

The solar abundance $\log A_{Sc} = 3.10$ is taken from Anders and Grevesse (1989). Hyperfine structure is not accurately known for the lines considered. It was taken into account in an approximate way, each line receiving an equivalent width dependent correction, estimated on the basis of approximate hyperfine structure data (Grevesse, private communication). The correction turned out to be fairly small (0.04 dex in the mean), justifying a posteriori such an approximate procedure.

Our results are plotted in Fig. 4, which show a clear but limited overabundance of Sc relative to Fe, amounting to

$[Sc/Fe] = +0.27 \pm 0.10.$

This value is only slightly lower than the determination of Paper I, the choice of a lower solar abundance in our previous analysis being partly compensated by the neglect of hyperfine structure. We thus confirm the overabundance of Sc relative to Fe, in disagreement with the differential analyses of metal-poor giants (Luck and Bond, 1985; Gilroy et al., 1988). We tentatively attribute this discrepancy to the (now much discussed) systematic errors in the differential analyses of extremely weak-lined stars relative to the sun. A more detailed discussion may be found in Zhao and Magain (1989).

3.5. Titanium

Ti I having only one weak line measurable in our green spectra and the Ti II oscillator strengths being of very low accuracy, no significant comparison with the much superior results of Paper I can be made.

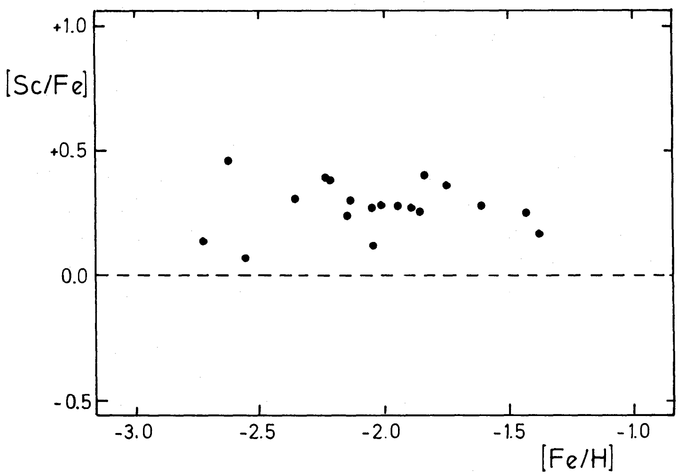

Fig. 4. [Sc/Fe] versus [Fe/H]. The present results are combined with those of Paper I. See text for further details

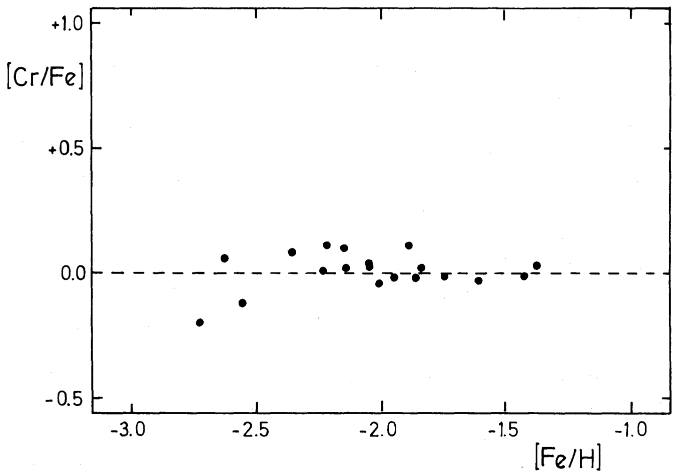

Fig. 5. [Cr/Fe] versus [Fe/H]

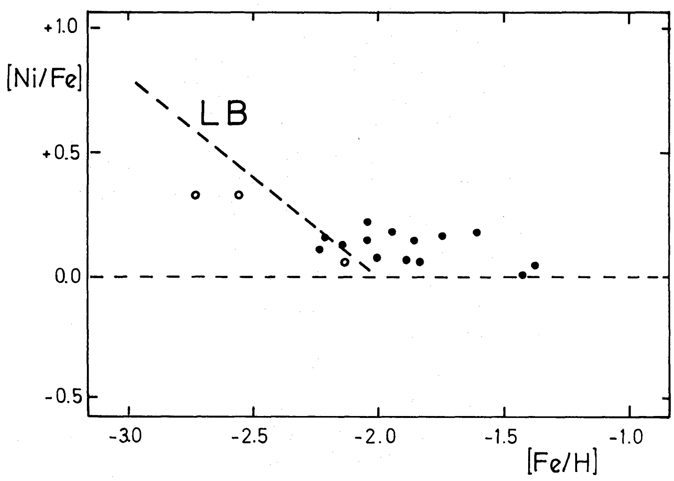

Fig. 6. [Ni/Fe] versus [Fe/H]. Open symbols indicate less accurate values. The mean trend found by Luck and Bond (1983, 1985) is indicated by the dashed line

3.6. Chromium

As for Ti II, the Cr II oscillator strengths are very poorly known. This is not the case for Cr I, however, and the presence of six weak neutral lines allows to derive an accurate chromium abundance. The results are shown in Fig. 5. We obtain

$$[\mathrm{Cr/Fe}] = +0.01 \pm 0.08$$

in perfect agreement with the results of Paper I, and no clear evidence for any cosmic scatter.

3.7. Nickel

The case of nickel has attracted some attention since the work of Luck and Bond (1983, 1985) who reported an unexpected overabundance of Ni relative to Fe in extremely metal-poor giants ([Fe/H] $\lesssim -2$). However, further investigations were not able to confirm this result, which is thus not accepted by the majority of authors (see Lambert, 1989 and Wheeler et al., 1989 for recent reviews).

The abundance of nickel is deduced from five weak lines with oscillator strengths determined from the solar spectrum, adopting a solar abundance $\log A_{\mathrm{Ni}} = 6.25$ (Anders and Grevesse, 1989) and a damping enhancement factor $f_6 = 1.75$ (Magain, 1985). As in Paper I, the Holweger-Müller (1974) model is adopted in the solar analysis.

Our results are plotted in Fig. 6 and compared with the mean trend in Luck and Bond's data. For the two stars with [Fe/H] < -2.5 which are included in Fig. 6 (HD 140283 and BD +2°3375), only three very weak lines have been measured. The dispersion of the individual line abundances is of the order of 0.2–0.3 dex. These two points are thus rather uncertain and systematic overestimates cannot be excluded. However, in view of these limited results, we would recommend not to discard Luck and Bond's results too readily: the abundance of nickel in extremely metal-poor stars certainly deserves more investigations.

For the 14 stars with more reliable results (filled circles in Fig. 6), we obtain a slight overabundance of nickel with respect to iron:

$$[\mathrm{Ni/Fe}] = +0.12 \pm 0.06$$

with a very small scatter and a marginal tendency for [Ni/Fe] to increase as [Fe/H] decreases.

3.8. Yttrium

Two weak Y II lines are present on the green spectra. However, they are so weak in many cases that they provide by themselves no reliable information for a large fraction of the program stars. Our results for the yttrium abundance in halo dwarfs can however be improved by considering the four lines measured on the blue spectra together with the two present lines. In order to avoid systematic errors, only the lines with equivalent widths larger than 10 mÅ are considered. Yttrium abundances are then available for 16 stars and are plotted in Fig. 7. A solar Y/Fe ratio is obtained for all but two stars.

The first of these, HD 74000, presents an overabundance of yttrium, but the scatter of the results from individual lines is very large (0.4 dex, the largest in this analysis). This result is thus rather uncertain (see next section, however).

The second star showing a non-solar Y/Fe ratio is HD 140283, the most metal-poor star for which we could determine the Y abundance. Although this result is based on a single line, arguments for its reliability were given in Paper I. This low value confirms the drop in the s elements abundances observed at very low metallicities (Spite and Spite, 1978, 1985).

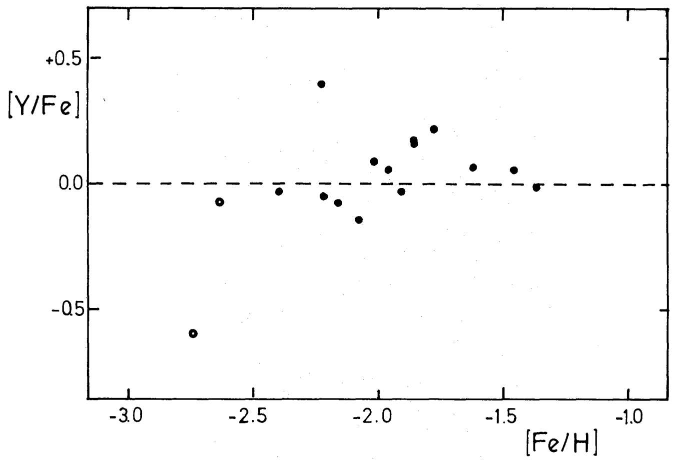

Fig. 7. [Y/Fe] versus [Fe/H]. The present results are combined with those of Paper I

Excluding these two stars, we obtain

$[Y/Fe] = +0.03 \pm 0.11$.

3.9. Barium

The barium abundance in extremely metal-poor dwarfs is generally (as in Paper I) determined from the resonance line of Ba II at 4554 Å. This line being rather strong, situated in a crowded spectral region and affected by hyperfine structure, a confirmation from the analysis of other lines is much wanted. We could detect the weak excited line at 5853 Å in 14 stars, with $[Fe/H] \geqq -2.2$. The oscillator strength of this line is well known (Wiese and Martin, 1980) and its hyperfine structure can be neglected (Holweger and Müller, 1974), especially in view of the weakness of the line in our program stars. For the metallicity range covered by these 14 stars ($-2.2 < [Fe/H] < -1.4$), we obtain a mean overabundance of

$[Ba/Fe] = +0.08 \pm 0.18$.

This is value slightly lower than the value obtained in Paper I for the same metallicity range, but the scatter is quite large in both cases (Fig. 8). It is of course very unfortunate that the 5853 Å line cannot be measured in the stars showing the drop in s elements abundances ($[Fe/H] \lesssim -2.3$).

The discrepancy between the two lines as well as the larger-than-usual scatter certainly call for more investigations. Some insight as to the cause(s) of these discrepancies may be gained by plotting the difference in abundance (resonance line minus excited line) as a function of the various atmospheric and line parameters. Figure 9 shows this abundance difference plotted versus the star's surface gravity. A strong correlation is obvious, the resonance line indicating higher abundances in stars with low surface gravity. Similar plots as a function of effective temperature, metallicity or line equivalent width show no such correlation. Errors in the adopted damping constant for the stronger line might have been suspected to lead to such an effect, but simulations showed this not to be true. We could not find any obvious way of fiddling with the parameters in order to get these line abundances agree with each other.

According to Cowley and Frey (1989), the 5853 Å line is blended with a high excitation Fe I line. If this neutral line would contribute significantly to the equivalent width, a correlation of abundance with surface gravity might be expected. However, we estimate the error on the barium abundance due to this blend not to exceed 0.1 dex in the worst cases. This is much too small to explain the observed trend.

Indeed, such a correlation is reminiscent of departures from LTE, as was already concluded in the case of Mg I (Paper I). In the case of Ba II, however, although the correlation is even stronger than for Mg I, the conclusion seems less obvious. It is not clear which of these lines would be affected by departures from LTE: plots of [Ba/Fe] versus surface gravity reveal the effect to be due to both lines showing correlations in opposite directions. Moreover, one would naively expect the abundances deduced from the two lines to agree in stars with high surface gravity, whereas these show an offset of the order of 0.2 dex.

Again, the highest value of [Ba/Fe] is obtained for HD 74000, confirming the result for yttrium. This nitrogen-rich star shows overabundances for some other elements, notably Na and Al (see Paper I and Sect. 3.2 above). Note, too, that the highest [Zr/Fe] was also found for this star (Paper I). HD 74000 might thus be considered as a mild barium dwarf of Population II. This would suggest a relation between the nitrogen and s-elements enhancements. Thus, if barium stars are the result of mass transfer in binary systems, the same explanation might apply to the nitrogen-rich stars (see Smith, 1987, for a discussion of nitrogen-rich stars).

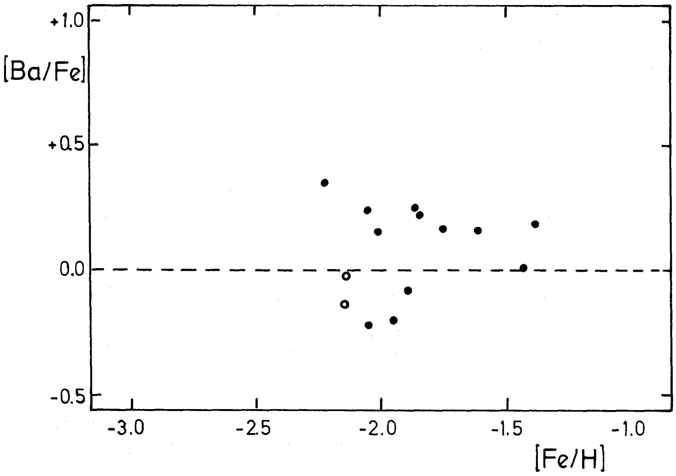

Fig. 8. [Ba/Fe] versus [Fe/H]

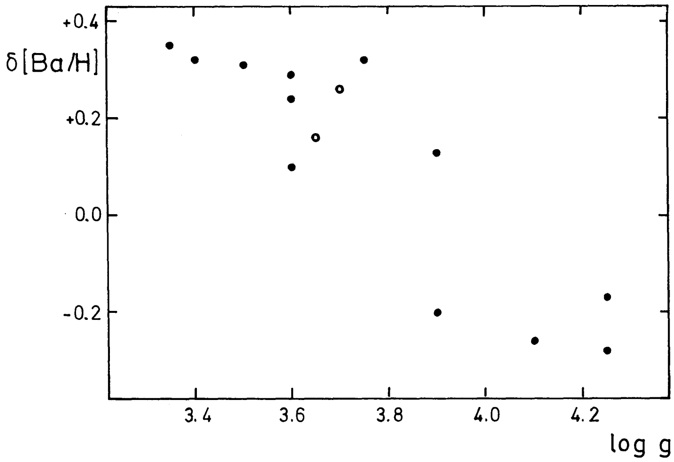

Fig. 9. Difference in Ba abundance as deduced from the excited and resonance line as a function of the star's surface gravity

4. Concluding remarks

In our opinion, the main conclusion which should be drawn from this and other recent works is the following. As more accurate data are available, more and more inconsistencies are found between the abundances indicated by different lines of the same element or between the abundance ratios in different stars. Let us just recall the comparison of different Mg I lines in Paper I or the similar comparison of Ba II lines in the present paper, which show discrepancies varying as a function of the star's surface gravity. Another possibly related effect is the scatter in [Ca/Fe] discussed in Sect. 3.3. Also, the large overabundance of Na relative to Al, when deduced from the resonance lines of both elements, might indicate a similar problem.

Whether these effects are due to departures from LTE or to another cause cannot be decided on the basis of the present data.

More investigations are obviously needed, both on the theoretical and on the observational side, before most abundance results can be fully trusted.

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