NON-LTE EFFECTS AND ABUNDANCE ANALYSES OF HALO STARS (*)

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ABSTRACT. The possible existence of departures from LTE affecting the abundance analyses of halo dwarfs and subgiants is analysed from the observational point of view, and illustrated by the case of the intermediate halo subgiant HD 76932. High resolution and high S/N Reticon and CCD spectra have been obtained with the ESO Coude Echelle Spectrometer. A detailed model atmosphere analysis has been carried out, which reveals a number of inconsistencies. In particular, the iron abundance derived from the neutral lines shows a very clear excitation potential dependence. Similar effects appear for oxygen and calcium and, possibly, for magnesium, chromium and ionized iron. Some overionization also seems to be present in a number of elements. The impact of these effects on the derived abundances may be rather large (some 0.2 to 0.6 dex). In particular, doubts might be raised about the reality of the oxygen overabundance and the odd-even effect in Na, Mg and Al.

1. INTRODUCTION

The use of solid-state detectors has allowed dramatic improvements in the quality of the spectroscopic data available for abundance determinations in Pop II stars. New, more precise analyses have shown clear variations of some relative abundances with overall metallicity, which have important implications for the chemical evolution of the Galaxy. All these analyses, however, are based on the assumptions of local thermodynamic equilibrium (LTE) and plane parallel model atmosphere, which we will refer to as the "classical" assumptions. Although the quality of the presently available data allow these assumptions to be tested, little effort has been done in that direction. The aim of this paper is to present the main results of such a test on the bright halo subgiant HD 76932.

(*) Based on observations collected at E.S.O. (La Silla).

G. Cayrel de Strobel and M. Spite (eds.), The Impact of Very High S/N Spectroscopy on Stellar Physics, 485–492.

2. OBSERVATIONS AND METHOD OF ANALYSIS

The observations were carried out at ESO (La Silla), with the Coude Echelle Spectrometer (CES) fed by the 1.4 m Coude Auxiliary Telescope. A total of 25 spectral regions were observed, either with the long camera and Reticon or with the short camera and CCD. The resolving power was set to 80000 and the S/N was generally higher than 200. The spectra were reduced with the IHAP facility at La Silla.

The Strömgren b-y and β indices as well as the Johnson V-K and spectrophotometric data all agree to indicate an effective temperature of 5815 (±15) K. The surface gravity, as determined by comparing the wings of strong lines to weak lines originating from the same atomic levels (Blackwell and Willis, 1977), is log(g) = 4.1. A microturbulent velocity of 1.2 km/s is deduced from Fe I and Ca I lines with accurate oscillator strengths.

The temperature structure of the model was chosen as:

$$T(\tau) = T_{*}(\tau) / T_{\odot}(\tau) \times T_{HM}(\tau) \qquad (1)$$

where τ is the optical depth at 500 nm, $T_{*}(\tau)$ and $T_{\odot}(\tau)$ are the temperature distributions of the theoretical models for the star and sun, and $T_{HM}(\tau)$ the temperature distribution of the solar Holweger - Müller (1974,HM) model. The theoretical models are from Magain (1983) and are computed with the MARCS program (Gustafsson et al., 1975). Eq. (1) means that the whole model grid is changed so that the grid solar model agrees with the HM model. This model was found to give the best fit of the strong line profiles. It must be pointed out, however, that none of the conclusions of this paper would be changed by the use of a purely theoretical model.

For each line, an element abundance is deduced from the measured equivalent width, under the assumption of LTE. Whenever available, accurate laboratory gf values are used, especially those of the Oxford group (Blackwell and collaborators). Otherwise, they are derived from the solar spectrum, but only if the solar line is found to be reasonably unblended and has a sufficiently well defined local continuum. The solar analysis is carried out with the HM model.

3. RESULTS

The Fe abundance is plotted as a function of the line excitation potential EP in Fig. 1, for both Fe I and Fe II. It appears that:
(1) all Fe I lines with EP < 2.6 eV indicate the same abundance, with a very small scatter (σ = 0.029 dex, which reduces to 0.023 if one discrepant line is excluded);
(2) the Fe I lines with EP > 2.8 eV give an abundance which increases with increasing excitation potential;
(3) the Fe II lines, all having EP > 2.8 eV, essentially show the same effect as the high excitation Fe I lines.

Similar effects appear for O, Mg, Ca and Cr, all showing a line abundance increasing with EP. The only clear exception is Ti (Fig. 2),

https://doi.org/10.1017/S0074180900035531 Published online by Cambridge University Press

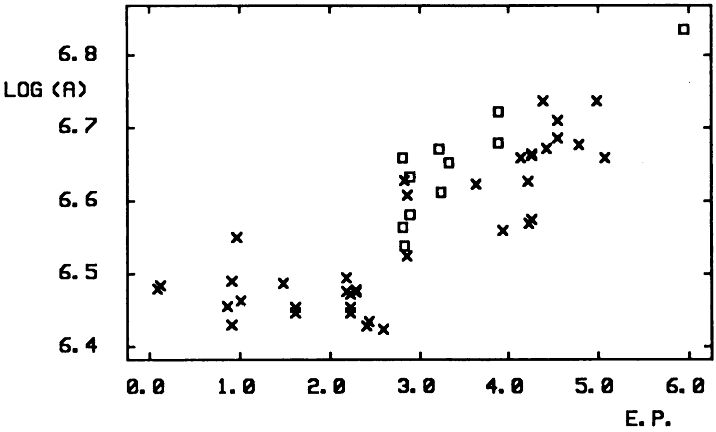

Figure 1. The computed Fe abundance is plotted versus the excitation potential for neutral lines (crosses) and ion lines (squares).

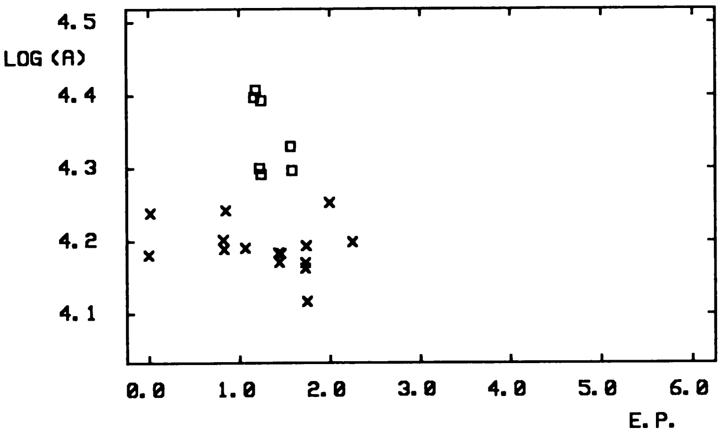

Figure 2. Same as Fig. 1 for Ti I (crosses) and Ti II (squares).

for which the deduced abundance is independent of EP, but which shows a rather strong overionization effect.

If these effects are the signature of model problems (such as temperature inhomogeneities), one might expect similar trends in all elements. On the other hand, if they are due to departures from LTE, a more erratic behaviour from element to element would be expected. The data show that the trend is remarkably similar for most elements, the slope of the log(A) - EP relation being close to 0.06 eV^{-1}. This would point to model problems, were it not for Ti I and the low excitation Fe I lines, which show a drastically different behaviour (slope $\approx$ -0.01 eV^{-1}). The conclusion is thus unclear: the data show definite departures from the classical assumptions, but do not allow to decide which one has to be relaxed. Maybe both are wrong!

4. CONSEQUENCES FOR ABUNDANCE DETERMINATIONS

Once it has been established that there are significant variations in the deduced abundances with excitation potential or with ionization stage, it is of interest to investigate the consequences of these variations for the abundance determinations.

The abundances deduced from different sets of lines are listed in Table I for the elements considered. For most of them, the uncertainties are quite large, ranging from 0.18 dex (Fe) to 0.59 dex (O). The discrepancies in the element abundances deduced from different lines are, at least in some cases, of the same order as the variations in relative abundances interpreted as signatures of galactic evolution. It cannot thus be excluded a priori that some of these trends just reflect errors in the spectroscopic analyses, and have nothing to do with galactic evolution. Let us illustrate this point by two specific cases.

Table I. Element abundances as given by different sets of lines

Element	EP	[el/H]	Element	EP	[el/H]
O I	0.0	-0.96	Ti I	0.0-2.3	-0.89 (±0.02)
	9.1	-0.37 (±0.03)	Ti II	1.1-1.6	-0.70 (±0.04)
Mg I	0.0	-1.00	Cr I	0.9-3.2	-1.15 (±0.05)
	4.3-6.0	-0.66 (±0.11)	Cr II	3.8-4.1	-0.96 (±0.06)
Ca I	0.0	-0.94	Fe I	0.0-2.6	-1.21 (±0.01)
	2.5	-0.79 (±0.03)		2.8-5.1	-1.04 (±0.03)
Ca II	7.5	-0.40	Fe II	2.8-6.0	-1.03 (±0.05)

Note: the listed uncertainty is twice the standard deviation of the mean value.

One very well established effect is the overabundance of oxygen relative to iron in metal-poor stars. In Fig. 3, [O/H] is plotted as a function of [Fe/H] according to the classical paper of Sneden et al. (1979). The oxygen abundances are deduced from the high excitation infrared triplet around 777 nm. The point corresponding to HD 76932, with the oxygen abundance deduced from the same lines, agrees very well with the general trend. Now, if the oxygen abundance was determined from the forbidden 630 nm line, nearly nothing would be left of the overabundance. (Imagine all the points with [Fe/H] < -1 moving down by a similar amount). Since there are some reasons to think that the forbidden line is a good abundance indicator, while the infrared triplet might possibly be affected by departures from LTE, it may not be unreasonable to question the reality of the oxygen overabundance.

Another interesting consequence of our results concerns the odd-even effect in the carbon burning products. Although the detailed behaviour of [Na/Mg] and [Al/Mg] in Pop II stars is subject to some controversy (see, e. g., Magain, 1987), it is generally agreed that Na and Al are overdeficient with respect to Mg, at least by some 0.5 dex.

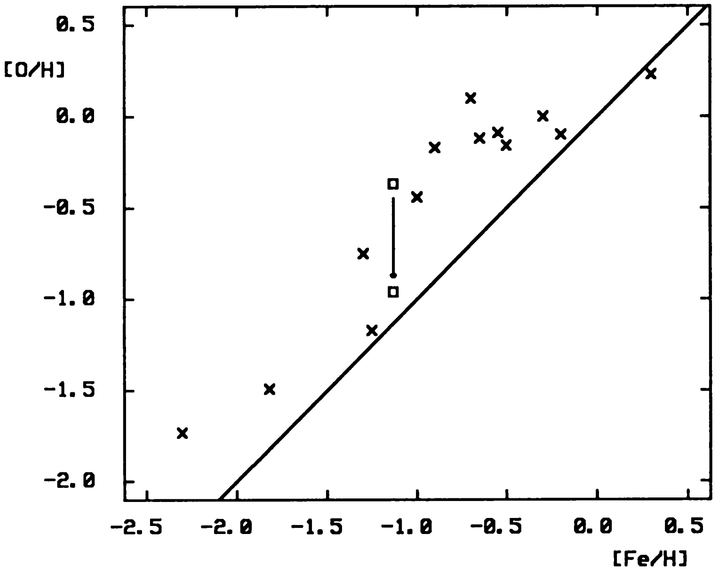

Figure 3. The oxygen abundance in HD 76932 as deduced from the infrared triplet (upper square) and from the forbidden line (lower square) is compared with the results of Sneden et al. (crosses).

The HD 76932 line abundances of Na, Mg and Al relative to H are plotted in Fig. 4 as a function of the line EP. The points for Na and Al fall on the curve defined by the Mg lines. This means that if the abundances of these elements were deduced from lines of the same excitation potential, it is likely that the odd elements overdeficiency would disappear. The reality of the enhanced odd-even effect in Pop II stars could thus also be questioned.

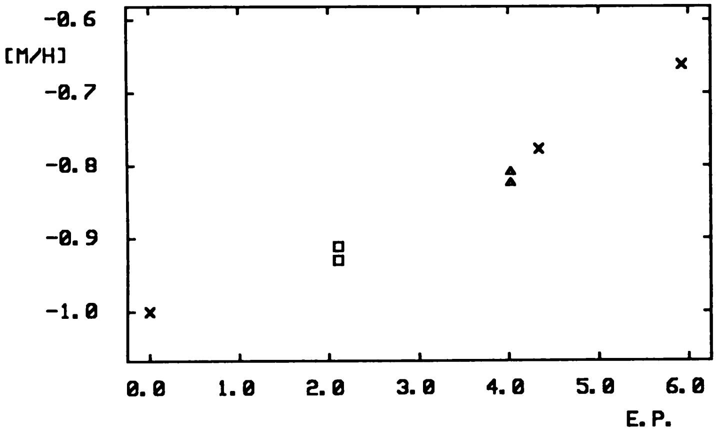

Figure 4. The deficiencies in Na (squares), Mg (crosses) and Al (triangles) are plotted versus the line excitation potential.

6. CONCLUSIONS

It is by no means our intention to conclude that the non-zero relative abundances found in Pop II stars just reflect departures from LTE or other flaws in the classical spectroscopic analyses. After all, HD 76932 might not be representative, and it cannot be excluded that the effects found in this analysis are just due to some peculiarity of that star, like binarity (but is it a peculiarity ?). However, as far as we know, no evidence for any peculiarity of HD 76932 has been reported. Nevertheless, it is urgently needed to analyse other stars, in order to confirm these results and to investigate the variations of these effects with temperature, gravity and metal abundance.

Although it might turn out that the classical LTE analyses are not always as bad as would appear from this paper, we have shown, at least, that some non-LTE effects may be present in the atmospheres of Pop II stars, and may have important consequences as far as the relative abundances are concerned. The solution of this problem is in our hands: we have the instruments to investigate these effects and the theoreticians are beginning to have the appropriate non-LTE codes. It is just a matter of will: do we intend to continue to provide the galactic evolution theorists with data we cannot reasonably guarantee their reliability, or will we concentrate part of our efforts on checking the validity of our assumptions?

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https://doi.org/10.1017/S0074180900035531 Published online by Cambridge University Press

DISCUSSION

BECKMAN How would the effects you discuss affect the derivation of the Li, Be and B abundances for HD 76932 ?

MAGAIN It is impossible to give a definite answer. But, since the lines used are all resonance lines, if these elements follow the general trend of increasing abundance with excitation potential, one might expect an eventual underestimate of these abundances. All this is, however, highly speculative.

PETERSON How did you determine T_{eff} ? Wouldn't choosing a higher T_{eff} alleviate this dependence of abundance on excitation potential ?

MAGAIN The effective temperature was determined from 3 colour indices plus spectrophotometric observations, all giving the same value within 20K. To reproduce the trend shown by most (but not all) elements, one would need to increase T_{eff} by some 300 to 400K. Such a high temperature would be completely incompatible with the colours as well as with the Hα wings. Moreover, it would introduce other problems (i.e. in the TiI excitation equilibrium).

GUSTAFSSON For 8 metal poor dwarfs with $T_{eff} \approx 6000K$ and $-0.8 \geq$ [Fe/H] ≥ -1.0 which we have analysed in our survey project (Andersen et al., this volume), we have around 20 Fe I lines with $W_\lambda < 50$ mÅ, spanning a range in χ_1 from 2eV to 5eV. From these lines we find similar slopes, positive for all the stars, with a mean of $\delta[Fe/H]/\delta\chi = 0.05$ eV^{-1} and a scatter of ± 0.01 eV^{-1}. Also our effective temperatures are determined from photometry.

MAGAIN I am pleased by this confirmation of my findings, which indicates that HD 76932 does not show a peculiar behaviour in that metallicity range.

BESSELL

1. There are significant differences between the T–τ relations of solar and low metal abundance models. What models do you use ?
2. What temperature calibration do you use ? (Your analysis of HD 140283 used an effective temperature and gravity different from that used by Peterson, Bessell and Norris, and Spite.Spite.)
3. Bessell and Norris use low excitation lines of NH and OH in the UV to derive abundances for O and N and obtain the same trends of O/Fe, N/Fe as seen in other data using the OI lines.

MAGAIN

1. I use a kind of scaled HM model, but taking into account the differences in T_{eff}, log g <u>and</u> [Fe/H], so this is a model which is adapted to metal-poor stars. But I have checked that my conclusions do not change if I use a theoretical stellar model instead.
2. I use my own calibrations of V–K and b–y (Astron. Astrophys. <u>181</u>, 323), which are based on the IR flux method. These calibrations essentially agree with those of Carney (differences of less than a few tens of K). The present analysis is completely independent from my previous work on HD 140283.
3. Around [Fe/H]$\approx$–1, I would not give too much weight to determinations based on the UV spectral region, because of problems in locating the continuum. However, I fully agree that it would be very interesting to

have comparisons with abundance determinations from molecules. A caution about the use of gravities determined from ionization equilibria : departures from LTE in the latter could cause large systematic errors in abundances derived from molecules.

RUTTEN Since you have lines from different wavelength regions, it may be interesting to plot abundance values against upper-level excitation energy instead of lower-level excitation energy, and to see whether the spread changes. If so, this is a NLTE diagnostic because ionization departures affect both levels and therefore only the opacities, while excitation departures due to photon losses (which I would suspect here) affect only the upper-level population and the line source function.