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Abundances of light elements in halo dwarfs: a re-analysis

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Summary. The abundances of a few light elements in the atmospheres of halo dwarfs are redetermined on the basis of literature data reanalysed in an homogeneous way. It is shown that the scatter of the resulting Mg and Al abundances is strongly reduced and that no discrepancy remains between the abundances deduced from blue and red lines. Mg, Si and Ca show constant overabundances while the Al overdeficiency seems in agreement with the predictions of explosive carbon burning.

Key words: stellar abundances – Population II stars – chemical evolution of the Galaxy

1. Introduction

Most recent abundance analyses of halo stars have focused on the light elements, from carbon to calcium. This is mainly because the variation of their abundances with time, or with overall metallicity, provides rather direct constraints on the models of galactic evolution. However, despite the improvement of the observational techniques, mostly by the use of efficient detectors, the situation is still rather confused. Recent review papers (Spite and Spite, 1985; Lambert, 1986) have discussed the available data and we shall not duplicate their discussions here, but rather briefly summarize the main results for the elements Na, Mg, Al, Si and Ca.

(1) It seems well established that the "even" elements Mg, Si and Ca are overabundant with respect to Fe in the halo stars (which means, in fact, that they are not as depleted as Fe in halo stars, when compared to disk stars). However, although the most recent analyses show some improvement, the scatter is large and it is not yet known whether that scatter is real (i.e. cosmic) or reflects inaccuracies in the abundance analyses.

(2) It is still an open question whether the overdeficiency of the "odd" elements Na and Al with respect to Mg increases with decreasing metallicity, as was argued by Peterson (1978) and confirmed by Arpigny and Magain (1983) in the case of Al. Some recent analyses (e.g. François, 1986a,b) seem to indicate a constant value of [Na/Mg] and [Al/Mg] in the halo, although lower than the solar value.

(3) It has been pointed out (Spite and Spite, 1985) that the analyses using blue or violet lines seem to give systematically lower abundances for Mg and Al than the analyses based on red lines. This would presumably indicate non-LTE effects in the atmospheres of the halo stars and would cast doubts on the LTE results for these particular elements, especially in view of the fact that we have no obvious reason to prefer a priori one set of lines, either blue or red.

These unsatisfactory points have led us to reanalyse the existing data for some halo stars, in an homogeneous way, in an attempt to clarify the situation. In particular, it is interesting to know if a careful homogeneous analysis of the available observational data is able to significantly reduce the scatter of the resulting abundance ratios. It is also of interest to re-examine the trends of [Na/Mg] and [Al/Mg] in the halo stars and the discrepancy between blue and red lines.

2. Method of analysis

2.1. General method and stellar sample

As already stated in the Introduction, our study is based on data gathered from the literature and reanalysed in an homogeneous way. As most recent analyses, it is a "line-by-line" model atmosphere analysis, the abundances being computed for each line from the observed equivalent width, the results for individual lines being subsequently averaged. It makes, as usual, the assumption of local thermodynamic equilibrium (LTE) and is based on a grid of model atmospheres computed by Magain (1983), with a version of the MARCS programme (Gustafsson et al., 1975). In order to fit that grid of models, we restrict our analysis to the dwarfs and subgiants hotter than 5000 K and with iron abundance lower than [Fe/H] = −1.

2.2. Data selection

We use equivalent widths published before July 1986. All lines with unreliable equivalent widths (due to blends or ill-defined local continuum) are rejected. We use laboratory oscillator strengths as far as possible. If the last ones are unavailable or of insufficient quality, we derive the oscillator strengths from the solar spectrum, provided that the solar lines are unblended and sufficiently weak for a reliable gf value to be determined (otherwise, the lines are rejected as well). The solar oscillator strengths are determined with the help of the Holweger-Müller (1974) model, with a microturbulent velocity of 0.82 km s^{-1}.

Whenever possible, we also reject the lines with stellar equivalent widths larger than 70 mÅ, on the basis of their high sensitivity to microturbulence and relative insensitivity to the element abundance (the exception being when only stronger lines are available, as for Al in the stars more metal-poor than [Al/H] ~ -1.5). When several authors have published equivalent widths for the same star, we use a weighted mean, the weights being determined on the basis of the data quality (Magain, 1984).

2.3. *Details on the individual elements*

The iron abundance is determined from weak Fe I lines. Whenever available, Oxford oscillator strengths (Blackwell et al., 1982, and references therein) are used. At wavelengths larger than 5000 Å, some oscillator strengths have been deduced from a fit of the solar equivalent widths, using a solar abundance $\log A_{\mathrm{Fe}} = 7.68$, in the scale $\log A_{\mathrm{H}} = 12$.

Very few reliable data are available for the sodium lines. We only use the equivalent widths of François (1986a) for weak Na I lines, with the oscillator strengths of Wiese and Martin (1980) and a solar abundance $\log A_{\mathrm{Na}} = 6.32$ (Lambert and Luck, 1978).

The oscillator strengths for the weak Mg I lines are from Froese-Fisher (1975) or from the solar spectrum, with a solar abundance $\log A_{\mathrm{Mg}} = 7.62$ (Lambert and Luck, 1978).

The resonance line of Al I at 3944 Å is rejected as blended (Arpigny and Magain, 1983). The oscillator strength of the 3961 Å line is from Wiese and Martin (1980). The atomic data for the infrared Al I lines ($\lambda \simeq 8773$ Å) are derived from the solar line profiles, with an abundance $\log A_{\mathrm{Al}} = 6.49$ (Lambert and Luck, 1978). Furthermore, a comparison of the data from different authors (see Magain, 1984; Arpigny and Magain, 1983; Magain, 1986b) has shown that Peterson's (1978) equivalent widths for the violet Al lines are systematically too low by a significant amount for the 4 stars in common (HD 19445, HD 84937, HD 140283 and BD + 17°4708). All Peterson's equivalent widths for these lines have thus been rejected.

The atomic data for the Si I lines are determined from the solar profiles, with an abundance $\log A_{\mathrm{Si}} = 7.63$ (Lambert and Luck, 1978) while the Ca I oscillator strengths are taken from Smith and O'Neill (1975) or Smith and Raggett (1981), the adopted solar abundance being $\log A_{\mathrm{Ca}} = 6.36$ (Smith, 1981).

2.4. *Determination of the atmospheric parameters*

The atmospheric parameters needed to select the stellar model are determined in the following way.

The effective temperature is deduced from the $V-K$ and/or $b-y$ colour indices, using the new empirical calibrations of Magain (1986a).

The surface gravity is determined from the $(b-y, c_1)$ diagram, with the theoretical calibration of Relyea and Kurucz (1978). Although this calibration may be slightly in error, the abundances, being deduced from neutral lines, are relatively insensitive to the surface gravity.

The overall metal abundance is taken from the literature. Again, the results are not affected by any reasonable error on this parameter.

The microturbulent velocity is taken equal to $1.25\,\mathrm{km\,s^{-1}}$. Although we have argued in the past (Arpigny and Magain, 1983; Magain, 1985) that this parameter should be determined for each star, and not guessed, this is only possible with high quality data and might be dangerous with an inhomogeneous material as used here (it might introduce rather large random errors). The present analysis is thus based on the assumption that all halo dwarfs and subgiants in the temperature range considered have roughly the same microturbulent velocity.

3. Results and discussion

The stars considered, along with the adopted atmospheric parameters and derived abundances, are listed in Table 1. The quoted uncertainties just reflect the scatter of the results from the individual lines and, thus, are most probably underestimates of the total uncertainties on the computed abundances. They are computed in the following way.

If enough lines of the element considered are present, the error bar is just twice the standard deviation of the mean value.

If the number of lines is insufficient for a meaningful estimate of the standard deviation, we deduce this one from lines of other elements (as a mean of the standard deviations for all the elements which have a sufficient number of measured lines).

The literature data for [Mg/Fe] versus [Fe/H] are shown in Fig. 1, which is analogous to Fig. 1a of Spite and Spite (1985). A mean overabundance appears clearly, but the scatter is very large. When compared to the results of our reanalysis, which are plotted in Fig. 2, it is obvious that the scatter has been strongly reduced. In fact, the remaining scatter can be entirely explained by the observational uncertainties. The mean overabundance is:

$$[\mathrm{Mg/Fe}] = +0.4 \pm 0.1\,, \tag{1}$$

the quoted uncertainty being the standard deviation of the individual values, thus measuring the remaining scatter. Moreover, there is no measurable variation of [Mg/Fe], when [Fe/H] increases from -3.5 to -1.0. This remarkable constancy, along with such a small scatter, may be hard to explain if, as is generally believed, Mg and Fe are formed by different processes, in different objects, with different lifetimes. This is even more so if we realise that the halo stars now in the solar neighbourhood have most probably been formed in widely separated parts of the Galaxy. Finally, note that the very small scatter leaves no room for a discrepancy between stars analysed from red and blue lines.

In Fig. 3 are shown the literature data for [Al/Mg] versus [Mg/H], in analogy with Fig. 1b of Spite and Spite (1985), apart from the fact that these authors use Fe instead of Mg. We prefer the present plot in view of the comparison with the theoretical predictions, Al and Mg being formed by the same process. A mean overdeficiency of Al relative to Mg is obvious but, again, the scatter is quite large. The results of our reanalysis are plotted for comparison in Fig. 4. Once more, the scatter is considerably reduced and there is no obvious discrepancy left between red and violet lines: the results are compatible with a steady increase of the Al overdeficiency as the Mg abundance decreases, the slope being close to 0.5. This is in agreement with the computations of explosive carbon burning (Arnett, 1971), but in contradiction with some recent results which argue in favour of a constant overdeficiency of Al in the halo stars (see, e.g., François, 1986a). However, the present data do not allow to rule out a possible discrepancy between red and violet lines. The increasing Al overdeficiency might be simulated by a discrepancy between these lines, combined with the fact that the red lines are used for the less metal-poor stars, while the most extreme stars are analysed on the basis of the violet lines. This point obviously requires

Table 1. Element abundances

HD/BD	$T_{\rm eff}$	Log$g$	[Fe/H]	[Na/H]	[Mg/H]	[Al/H]	[Si/H]	[Ca/H]	Sources
19445	5850	4.2	−2.36	–	−1.79	−2.60	–	−1.89	1, 2, 5
			0.05	–	0.10	0.20	–	0.10	
64090	5340	4.2	−1.94	–	−1.44	−2.04	−1.68	−1.53	2, 6
			0.09	–	0.12	0.12	0.20	0.18	
74000	6120	3.9	−2.40	–	–	–	–	−1.77	2
			0.29	–	–	–	–	0.30	
76932	5810	3.5	−1.12	−0.89	−0.70	−0.90	−0.82	–	6
			0.09	0.08	0.06	0.09	0.06	–	
84937	6200	3.5	−2.43	–	−2.13	–	–	−1.91	2
			0.06	–	0.17	–	–	0.10	
94028	5910	3.8	−1.76	−1.61	−1.28	−1.30	−1.24	−1.34	2, 6
			0.09	0.07	0.08	0.15	0.26	0.11	
97916	6240	3.7	−1.28	–	–	−0.87	−0.73	−1.13	2, 6
			0.18	–	–	0.23	0.36	0.44	
105755	5670	3.0	−0.87	–	–	−0.62	−0.64	–	6
			0.10	–	–	0.06	0.12	–	
108177	6030	3.9	−2.01	−1.89	−1.77	–	–	−1.49	2, 6
			0.10	0.07	0.46	–	–	0.35	
134169	5780	3.4	−1.02	–	−0.55	−0.77	−0.70	–	6
			0.03	–	0.02	0.02	0.02	–	
140283	5630	3.2	−2.78	–	−2.39	−3.40	−2.19	−2.39	1, 2, 5, 6
			0.05	–	0.08	0.20	0.12	0.09	
160617	5920	3.3	−1.74	–	−1.48	−1.69	–	−1.09	7
			0.09	–	0.18	0.34	–	0.18	
211998	5200	3.7	−1.54	−1.67	−1.10	−1.59	−1.19	–	6
			0.07	0.11	0.10	0.07	0.05	–	
−10° 0388	5900	3.3	−2.70	–	−2.25	−3.53	–	–	4
			0.26	–	0.30	0.48	–	–	
+01° 2341	6220	3.7	−2.91	–	−2.48	–	–	–	3
			0.23	–	0.25	–	–	–	
+17° 4708	5960	3.5	−2.08	–	−1.56	–	–	−1.42	2
			0.10	–	0.30	–	–	0.10	
+20° 3603	6200	4.5	−2.49	–	−1.98	–	–	−2.09	2
			0.16	–	0.44	–	–	1.08	
+26° 3578	6140	3.5	−2.57	–	−2.20	–	–	−1.98	2
			0.14	–	0.40	–	–	0.16	
+34° 2476	6180	3.7	−2.38	–	−1.89	–	–	−1.80	2
			0.16	–	0.45	–	–	0.30	
+42° 2667	5950	3.8	−1.60	–	–	–	–	−1.02	2
			0.25	–	–	–	–	0.40	
G 64-12	6200	3.6	−3.61	–	−3.18	–	–	–	3
			0.14	–	0.16	–	–	–	

Notes to Table 1

The uncertainty, computed as explained in the text, is indicated below each element abundance.

The sources of equivalent widths are the following: (1) Aller and Greenstein (1960), (2) Peterson (1981) and references therein (3) Carney and Peterson (1981), (4) Barbuy et al. (1985), (5) Magain (1985), (6) François (1986a), (7) Perrin (1986)

further investigations. However, we have shown that the available data, when selected with care reanalysed homogeneously, do not indicate any obvious discrepancy, and, so, departures from LTE cannot be inferred from the presently available data.

A definite interpretation of these results in terms of nucleosynthesis would require a similar analysis of the Na/Mg abundance ratio. Unfortunately, the results for sodium are too scarce to confirm the trend shown by aluminium. Such a confirmation would be extremely valuable and the determination of the sodium abundance in halo stars should be included in future investigations.

For Si and Ca, we obtain overabundances comparable to that of Mg:

$$[\mathrm{Si/Fe}] = +0.4 \pm 0.15 \tag{2}$$

and

$$[\mathrm{Ca/Fe}] = +0.5 \pm 0.15. \tag{3}$$

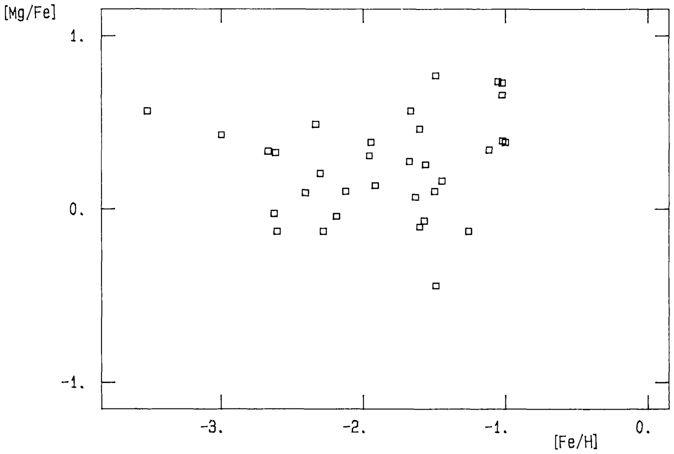

Fig. 1. Plot of [Mg/Fe] versus [Fe/H] for halo dwarfs, using literature data

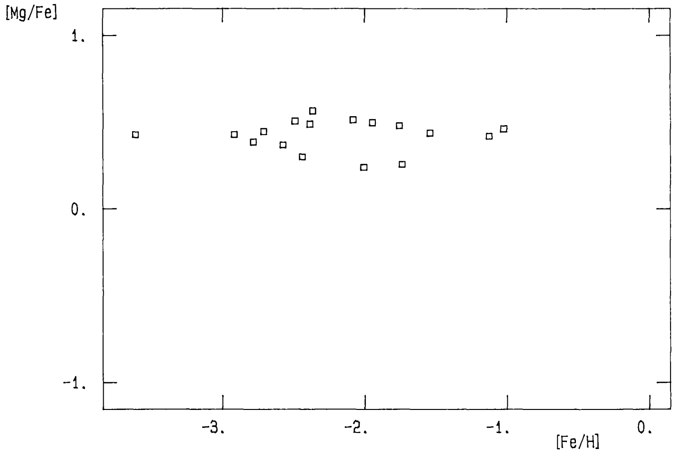

Fig. 2. [Mg/Fe] versus [Fe/H] as given by the present re-analysis

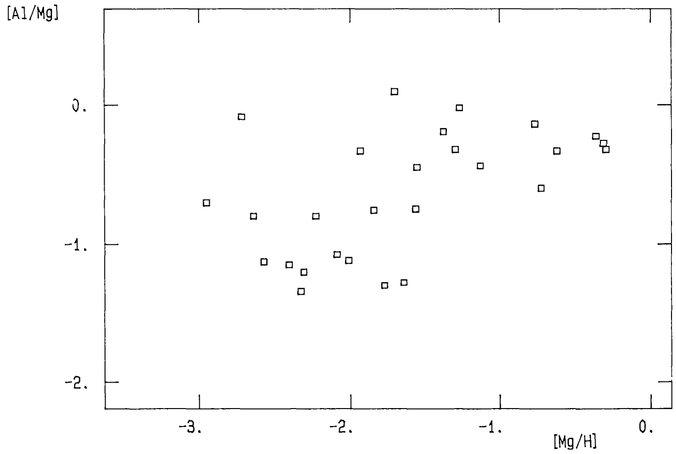

Fig. 3. Plot of [Al/Mg] versus [Mg/H] using literature data

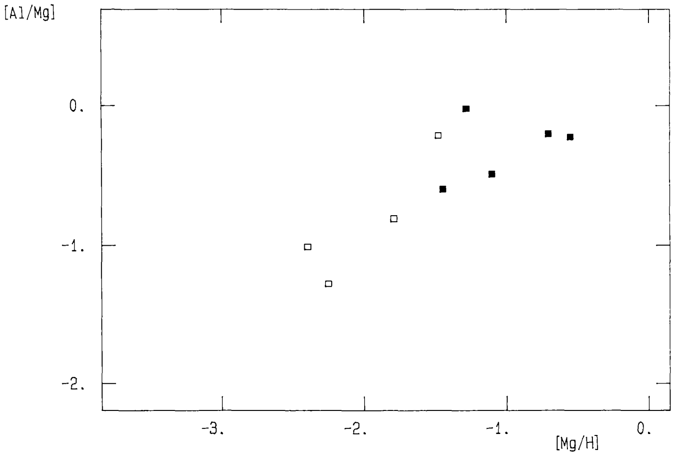

Fig. 4. [Al/Mg] versus [Mg/H] using the results of the present reanalysis. Open squares indicate the Al abundances deduced from the 3961 Å resonance line, while filled squares correspond to the abundances derived from red excited lines

Again, there is no obvious trend with [Fe/H] and the scatter can be entirely accounted for by the observational uncertainties.

4. Concluding remarks

We have shown that, by a critical selection of the existing data and a careful and homogeneous reanalysis, it was possible to remove some discrepancies and to reduce the scatter of the results when it was particularly large. No cosmic scatter is detectable and, so, if present, it should not exceed some 0.1 dex. This tends to indicate that the mixing of the halo material was quite efficient, even in the very early stages of the galactic evolution (at least if these stars are as old as is generally assumed).

The trends themselves may be summarized in the following way.

(1) The "even" (α) elements Mg, Si and Ca show a constant overabundance relative to Fe: $[\alpha/\mathrm{Fe}] \simeq 0.4 - 0.5$ for a wide range of Fe abundances ($-3.5 < [\mathrm{Fe/H}] < -1.0$).

(2) The overdeficiency of Al relative to Mg probably increases with decreasing Mg abundance, in agreement with the predictions from the theory of explosive carbon burning.

Of course, the improvements discussed here do not weaken the need for future investigations. The number of elements studied is small and the rather severe data selection has left us with relatively few stars. Also, the use of an inhomogeneous material, with very inhomogeneous quality, is an obvious weakness of this analysis. The next improvement will come from a careful homogeneous analysis of high quality homogeneous material.

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