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*Letter to the Editor*

# The Al/Mg abundance ratio in halo stars*

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Summary. The Al to Mg abundance ratio is redetermined in two extreme metal-poor stars, HD 19445 and HD 140283, on the basis of accurate spectral material. It is found that: (1) one of the two lines used for the Al abundance determination is blended by CH lines; (2) no anomalous difference appears between the hotter and the cooler star, both showing an Al overdeficiency; (3) the observations are in fair agreement with predictions from the theory of explosive carbon burning.

Key words: abundances – halo stars – nucleosynthesis

## 1. Introduction.

The Al to Mg abundance ratio is a key test of nucleosynthesis theories. These elements are generally believed to be formed through carbon burning, either during a hydrostatic phase or in an exploding supernova. Thus, as emphasized by Spite and Spite (1980), their abundances provide a fundamental clue for determining the physical conditions of this burning. Explosive carbon burning (ECB) has been studied by Arnett (1971). A very important outcome of these computations is that the abundance of Al relative to Mg is very sensitive to the primitive metal content of the supernova. Accordingly, the atmospheres of very metal-poor stars, which are believed to be formed out of gas ejected from metal-poor supernovae, should show a strong overdeficiency of Al relative to Mg, if ECB is responsible for the formation of these elements.

These results have led several investigators to analyse the Al to Mg ratio in stars of different overall metallicities. Peterson (1978b) determined the Al to Fe ratio in eleven metal-poor stars and found an overdeficiency of Al relative to Fe, increasing with the Fe deficiency. This, along with the assumption that Mg and Fe are deficient by the same amount, supports Arnett's computations. On the other hand, Spite and Spite (1980), analysing a sample of six metal-poor stars, found that Al, Mg and Fe are roughly deficient to the same degree, independently of the overall metal content. This contradiction raises some important questions. First, it would be very interesting to know whether this difference is real or if it is due to observational and/or analysis uncertainties. Second, if the difference is real, we would like to know why similar stars show such drastically different behaviours. Third, this difference could reflect different nucleosynthetic processes or differences in the physics of the stellar atmospheres. Noting that all their stars are cooler than Peterson's, Spite and Spite suggest that the difference could be due to diffusion processes occurring in the atmospheres of the hotter stars, which could lower the Al abundance. In that case the atmospheric composition of the cooler stars only would be representative of an initial composition and the observations would be in contradiction with the computations of pure ECB.

A number of problems hamper the determination of the Al abundance. The only Al lines measurable in the spectra of such metal-poor stars are the two resonance lines at 3944 and 3961 Å. These lines are still rather strong even in these stars, lying on the flat part of the curve of growth. Therefore, the deduced abundance is very sensitive to microturbulence and to errors in the equivalent widths. Furthermore, the Al I lines are situated in the wings of the very strong H and K lines of Ca II, although this latter effect is not very important in these stars. Finally, it is found that the abundance deduced from the 3944 Å line is generally greater than the abundance deduced from the 3961 Å line. As a matter of fact, while the 3961 Å line has an oscillator strength twice as large as that of the 3944 Å line, the latter is the stronger in the spectra of most metal-poor stars.

These many unsatisfactory points have led us to reanalyse carefully two very metal-poor stars, namely the well-known "subdwarfs" HD 19445 and HD 140283. The difficulties encountered in the determinations of the Al abundance have already been commented on by Pagel (1979) who classified this case as "unclear or ambiguous".

## 2. Abundance analysis.

The analysis is based on IIa-O plates taken by one of us (CA) at the Coudé focus of the 1.52 m telescope at the Haute-Provence Observatory, with a reciprocal dispersion of 12.4 Å/mm and a resolution of 0.25 Å. Nine good plates were available for HD 19445 and ten for HD 140283. These spectrogrammes were recorded with the Grant microphotometer and reduced with the HP 2100 computer at Liège. The different spectrogrammes were co-added, giving a signal-to-noise ratio better than 100. A more detailed description of the spectral material and reduction procedure will appear in a subsequent paper. The analysis was carried out with models computed with a version of Gustafsson's programme (Gustafsson et al., 1975). The effective temperature, surface gravity, microturbulence and Fe abundance were determined by an analysis of Fe lines (Magain, 1983) using the very accurate oscillator strengths of the Oxford group (Blackwell et al., 1982, and references therein).

The internal consistency of the equivalent widths,

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W, can be estimated from the scatter of the individual Fe I line abundances. For HD 19445, the dispersion in the log A's determined from 13 lines is found to be 0.23 dex when using Peterson's (1978a) W's, whereas it is only 0.05 dex when based upon the data of Magain (1983). Since, furthermore, no systematic difference was detected either between these two sets of data, or between our equivalent widths in general and those published in earlier studies, we feel we may safely conclude that our equivalent widths for the stars in question are the most accurate available up to now. This was achieved, in particular, by securing a sufficiently large number of good plates and taking advantage of the method of co-addition of spectra. On the other hand, as far as the Al lines themselves are concerned, although they fall near the wings of the H and K lines, the blending is by no means severe in the extremely metal-poor stars considered here and we feel confident that the Al abundance can be derived from the equivalent widths, without recourse to the construction of synthetic spectra. An example of intensity tracing in the region in question is shown in Fig. 1 for HD 140283. The situation for HD 19445 is very similar.

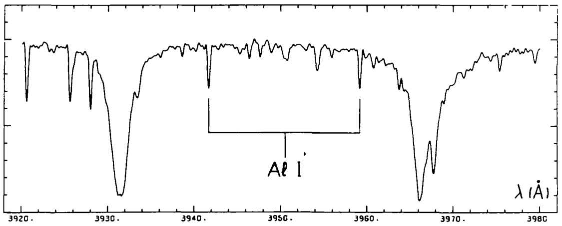


Fig. 1. Spectrum of HD 140283 in the region of the Al lines. This spectrum is actually the sum of 10 photographic spectra.

The equivalent widths of the lines used for the Al and Mg abundance determination are listed in Table 1. The oscillator strengths are taken from Froese-Fisher (1975) for Mg and from Wiese et al. (1969) for Al. The damping constants are computed with the usual Unsöld formula (Gray, 1976, see also Spite and Spite, 1980).

Table 1. Line data.

| Element | λ | W(19445) | W(140283) |
|---|---|---|---|
| Al I | 3944.0 Å | 140 mÅ | 95 mÅ |
| Al I | 3961.5 | 125 | 80 |
| Mg I | 4057.5 | 48 | 18 |
| Mg I | 4167.3 | 56 | 23 |
| Mg I | 4703.0 | 91 | 42 |

As expected, the two Al lines give very discordant results, the difference in abundance computed from the two lines amounting to 0.6 dex, which is far outside the usual errors in our analysis. A careful examination revealed that at a resolution of about 0.2 Å the 3944 Å line is blended by 4 lines belonging to the (0,0) band of the B-X system of the CH molecule ($Q_2$(14) at 3943.82, $P_2$(9) and $Q_1$(14) at 3943.92 and $P_1$(9) at 3944.18). The contribution from these lines was estimated by measuring other (unblended) lines from the same band. The computation of the equivalent widths of the blending lines is therefore straightforward - the relative strengths being simply related by

$$\log X = C + \log S_J - \theta \chi \qquad (1)$$

where log X is the abscissa of the curve of growth, $S_J$ is the Hönl-London factor, $\theta$ = 5040/T, where T is the excitation temperature and $\chi$ is the excitation potential. C is a constant which depends on the CH abundance and is determined by fitting the unblended lines to (1).

It is found that the correction to the 3944 Å equivalent width is of the order of 30 mÅ, which is just what is needed to bring the abundances computed from the two Al lines into good agreement. We therefore conclude that the 3944 Å line is significantly blended, within about 0.2 Å, by CH lines and should not be used in an abundance analysis. The Al abundance is thus deduced from the single 3961 Å line, which is found to be unblended. Of course, we included the extra opacity due to the Ca II H line wing, but the corresponding correction to the computed abundance amounts to, at most, 0.05 dex.

Table 2. Stellar abundances.

| $T_{eff}$ | log g | $v_t$ | [Fe/H] | [Mg/H] | [Al/H] | [Al/Fe] | [Al/Mg] |
|---|---|---|---|---|---|---|---|
| HD 19445 | | | | | | | |
| 5730 | 4.2 | 1.4 | -2.36 | -1.83 | -2.66 | -0.30 | -0.83 [a] |
| 5800 | 4.0 | 1.0 | -2.12 | -2.01 | -3.13 | -1.01 | -1.12 [b] |
| HD 140283 | | | | | | | |
| 5400 | 3.2 | 1.6 | -3.01 | -2.54 | -3.77 | -0.76 | -1.23 [a] |
| 5730 | 3.3 | 1.0 | -2.4 | -2.75 | -2.65 | -0.25 | +0.1 [c] |

Notes: [X] ≡ $\log(X_*/X_\odot)$ , a: this analysis (the solar Fe, Mg and Al abundances used are 7.65, 7.62 and 6.49 respectively, in the usual scale $\log N_H$ = 12.00), b: Peterson (1981), c: Spite and Spite (1980), published values.

As can be seen from Table 2, we derive an Al deficiency relative to Fe which is somewhere in between the results of Peterson (1978b) and Spite and Spite (1980). However, we find that Mg is overabundant relative to Fe and since the theoretical computations refer actually to the Al/Mg abundance ratio, it is this latter ratio itself, not the Al/Fe ratio, that should be used when making a comparison with the theory of explosive nucleosynthesis. This has been done in Fig. 2, in which we use [Mg/H] rather than [Fe/H] for the abscissa, as recommended by Arnett (1971), and which indicates that our results are in fair agreement with ECB predictions.

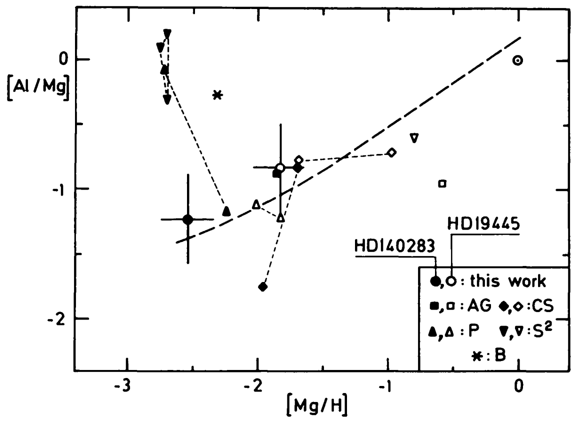


Fig. 2. [Al/Mg] versus [Mg/H] as derived from different analyses of HD 19445 (open symbols) and HD 140283 (filled symbols). AG = Aller and Greenstein, 1960; CS = Cohen and Strom, 1968; P = Peterson, 1978a and b, 1981; $S^2$ = Spite and Spite, 1978, 1980; B = Baschek, 1959. Dotted lines connect results obtained by the same author(s) using different equivalent widths, different atmospheric parameters or different methods of analysis. The dashed curve is drawn from Table 2 of Arnett (1971), reading [Mg/H] for [η] and corresponds to pure ECB; the predictions of partial ECB would fall above this line.

The error bars represent our best estimate for the r.m.s. variations in the abundance ratios obtained when allowing for plausible uncertainties in the equivalent widths, in $T_{eff}$, log g, microturbulence, the temperature structure of the models and the damping constants. Also plotted in this figure are the relative abundances derived in previous analyses and we can appreciate how right Pagel was when classifying the case of the Al abundance, as mentioned above.

## 3. Concluding remarks.

The relative Al and Mg abundances obtained for HD 19445 and HD 140283 by our analysis are consistent with the idea that ECB is a likely source for the production of Al and Mg in the early stages of galactic evolution. Moreover, an important consequence of our finding no peculiar difference between the two stars is that no special process seems to be needed to account for a separation between hotter and cooler stars. The interpretation of such a separation would indeed be very difficult, as already pointed out by Peterson (1981).

While one would certainly wish to verify or refine such statements on the basis of more stars and more elements, we wanted mainly to show here that, at variance with recent conclusions, no contradictory results are derived for two extensively studied, very metal-poor stars when a homogeneous, substantial material is used for both and both are treated and analysed in exactly the same manner.

Another significant result of our study is the explanation that we propose, in terms of a blending by CH lines, for the anomalous intensity ratio often observed for the Al I lines in metal-poor stars.

One may invoke several reasons to account for the discrepancy between the results of the different analyses. First, the blending of the 3944 Å line is more severe at lower temperatures. Indeed, if $T_{eff}$ is decreased from 6000 to 5500 K, for a given gravity, the number of CH molecules relative to Al I atoms is increased by roughly a factor 5. This may cause the Al abundance to appear higher in the cooler than in the hotter stars if the blends are not properly taken into account. Second, different authors adopt microturbulent velocities that may differ by 1 km/s or more: this may affect the Al abundance as the Al lines are very sensitive to this parameter. Third, while, for instance, Spite and Spite use, as we do, the unmodified Van der Waals damping constants, the values adopted by Peterson are increased by 0.7 dex over the Van der Waals value. Each of these differences may account for a difference of the order of 0.3 dex in the Al abundance. Finally, it seems that Peterson's equivalent widths for the Al lines are underestimated considerably. While her W's agree generally with ours, some lines, including the Al ones, are strongly discrepant, the difference being as large as 50 mÅ. This may be attributed in part to the difficulty of locating the continuum in the Echelle spectra and in part to the equivalent widths measurements via the line depth. This procedure is not valid for strong lines, where the damping wings contribute significantly to the equivalent width and vary generally from line to line.

Our Mg/Fe ratio also differs significantly from values found previously. This is due to our finding both a higher Mg abundance and a lower Fe abundance than previous authors. Since we use theoretical gf values for Mg, its higher abundance might be attributed to an error in their absolute scale. However, we have checked the Mg abundance by a differential analysis relative to the sun, using the single 4703 Å line (the other two being badly blended in the solar spectrum). Within the error bars, coming mainly from the uncertainty in the damping constant, the two analyses give the same Mg abundance. As for Fe, its abundance is discussed in Magain (1983) where it is shown that differential analyses of very metal-poor stars relative to the sun are subject to important systematic errors due essentially to the poor knowledge of the damping constants.

Thus, the discordance between the different authors appears to be due to the sum of a number of analysis uncertainties. At the risk of stating a truism, one could not stress too much the fact that (a) it is worth devoting considerable time and effort to secure enough observational material and to actually bring accidental and systematic errors to a minimum by appropriate reduction procedures and (b) only a very careful, critical analysis may lead to significant results. In particular, the various physical parameters should be determined as accurately as possible, rather than simply guessed (as is often the case for microturbulence and surface gravity). The results of abundance determinations are indeed very sensitive to the various uncertainties discussed above (to which we could add possible departures from LTE as well as temperature inhomogeneities!) and in conclusion, we fully agree with Spite and Spite (1980) to consider that "the errors in the abundance determinations are generally underestimated".

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