From Lithium to Uranium: Elemental Tracers of Early Cosmic Evolution
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Abundances in extremely metal-poor stars. Comparison of the trends of abundance ratios in giants and turnoff stars†

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Abstract. As part of a study of the detailed abundance patterns in extremely metal-poor stars, we have compared our samples of giants and dwarfs with two samples of dwarfs measured by different teams. For most elements the abundances are in good agreement, but for C, Na, and Al we show that the atmospheric abundances are different in dwarfs and in giants. For C the difference could be explained by "atmospheric effects" or by the influence of the first dredge-up, but for Na and Al deep mixing inside the stars must be invoked. Until now, such deep mixing has not been observed in metal-poor field stars. An excess scatter in [Mg/Fe] in giants remains unexplained.

Keywords. Stars: abundances, stars: atmospheres, stars: Population II, stars: subdwarfs, stars: supernovae: general, nucleosynthesis

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1. Introduction

After the pioneering work of McWilliam *et al.* (1995) and Ryan *et al.* (Ryan *et al.* 1996), several teams have recently studied the chemical composition of Galactic Extremely Metal-Poor (EMP) stars ([Fe/H] ≈ -2.5 or less). The chemical composition of the atmospheres of these stars is indeed a fossil record from which evidence on the earliest nucleosynthetic processes in the Galaxy may be obtained.

The advent of efficient high-resolution spectrographs on large telescopes, such as UVES at the 8m VLT (Dekker *et al.* 2000), HIRES at the 10m Keck telescope (Vogt *et al.* 1994), or UCLES at the 4m AAT, has made it possible to obtain high-resolution, high S/N spectra of quite faint stars. As a consequence, the recent studies represent significant

† Based on observations made with the ESO Very Large Telescope at Paranal Observatory, Chile (VLT Large Programme "First Stars", ID 165.N-0276, P.I. R. Cayrel).

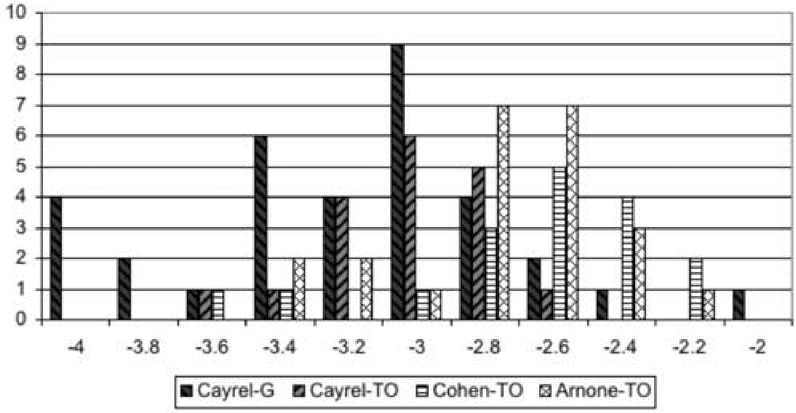

Figure 1. Metallicity distribution of the samples of EMP giants (G) and turnoff stars (TO). The Arnone *et al.* (2005) and Cohen *et al.* (2004) turnoff samples have $<$ [Fe/H] $> \simeq -2.7$, while our turnoff and giant stars (Cayrel *et al.* 2004) have $<$ [Fe/H] $> = -3.1$; overall, the four samples cover similar ranges in metallicity.

progress in the determination of precise abundance ratios and their interpretation in terms of early Galactic nucleosynthesis and the nature of the first supernovae.

In an earlier paper, we have studied the abundance ratios of the elements up to Zn as functions of [Fe/H] or [Mg/H] in a sample of EMP giants (Cayrel *et al.* 2004). For most of these non neutron-capture elements we found the abundance trends to be extremely tightly defined, but a few elements showed significantly larger scatter. It is clearly important to verify whether this scatter reflects processes in the early Galaxy or internal mixing in the stars. We do so by comparing our results for the giants with similar data for different samples of turnoff stars. E.g., [Na/Fe] in RGB stars could possibly vary due to deep mixing inside the star, even if this is not predicted by standard models, but this is practically impossible in turnoff stars. Here we discuss the trends of [C/Fe], [Mg/Fe], [Ca/Fe], [Na/Fe] and [Al/Fe] versus [Fe/H] in samples of EMP giants and turnoff stars.

A significant fraction of EMP stars are carbon-rich (∼20%–30%, depending on the level of C-enrichment; Beers, priv. comm.), including the two most iron-poor stars currently known ([Fe/H] < -5, Christlieb *et al.* 2002, Frebel *et al.* 2005); they are generally also enriched in O and N. These C-rich objects form a specific class of peculiar stars, which we do not discuss here.

In the following we compare the trends of abundance ratios observed in one sample of EMP giants and three samples of EMP turnoff stars, as detailed below. The metallicity distribution of the samples is shown in Fig. 1. All the abundance results were obtained from spectra with a resolution near 40,000 and high S/N ratio:

- Our programme at the ESO-VLT now includes a total of 52 normal EMP stars: 34 giants (Cayrel *et al.* 2004, Spite *et al.* 2005) and 18 turnoff stars (new results). The spectra cover the range 335-1000 nm almost completely, with $S/N \geqslant 200$ at 600 nm.
- The Keck Pilot Program (Carretta *et al.* 2002, Cohen *et al.* 2004) includes 15 EMP turnoff stars. The spectral coverage is 384-532 nm at $S/N > 100$.
- The Anglo-Australian (AAT) team (Arnone *et al.* 2005) studied a sample of 23 turnoff stars (and a few giants not considered here), in the spectral range 490-820nm and with $S/N > 100$.

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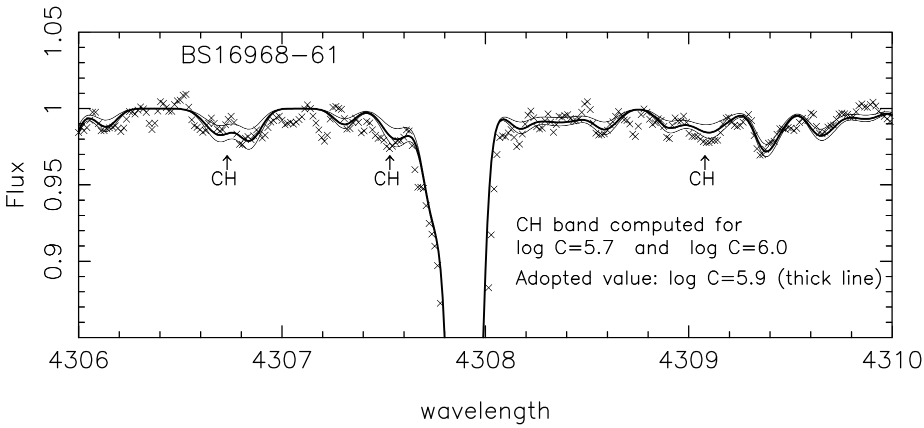

Figure 2. Spectrum of a turnoff star ([Fe/H]= -3.05) in the region of the G-band of CH. Synthetic spectra were computed for $\log \epsilon(\mathrm{C}) = 5.7$ and 6.0 (thin lines) as well as for $\log \epsilon(\mathrm{C}) = 5.9$ (adopted; thick line); we find [C/Fe] $\approx +0.45$.

The data in the different samples have been analysed in closely similar ways, always assuming LTE and adopting Kurucz or OSMARCS models. Effective temperatures were generally derived from colour indices (except that Hα line profiles were used for our turnoff stars), log g from the ionization equilibrium of Fe.

2. Carbon abundances

So far, C abundances in EMP turnoff stars have been measured only in our VLT programme. This measurement is difficult because the CH lines are very weak in these stars, and excellent S/N is needed (see Fig. 2).

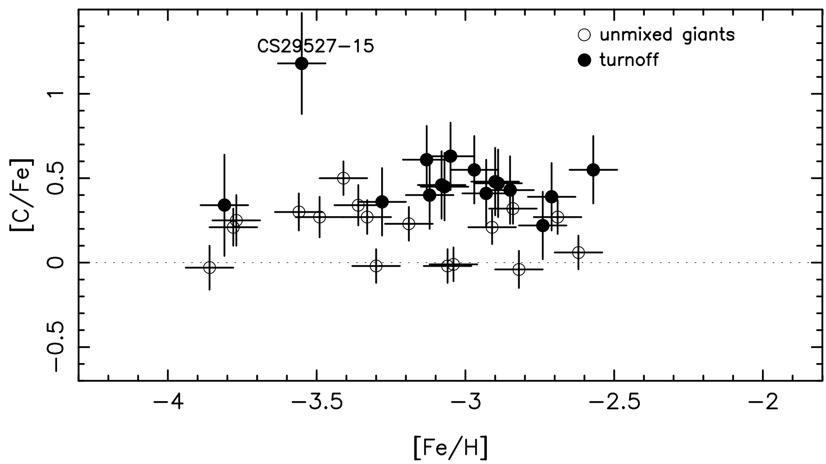

Figure 3. [C/Fe] vs. [Fe/H] for the VLT giants (open circles) and turnoff stars (filled circles). A systematic offset is seen between the two samples, but no significant trend with [Fe/H].

In giants the scatter in the [C/Fe] ratio is very large (Spite *et al.* 2005), but we have shown that it is caused by mixing between the H burning layer (where C is transformed

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into N by the CNO cycle) and the atmosphere of the star. The giants could be divided into two classes, where the "mixed" stars have high N and ^{13}C abundances and are mainly found on the upper part of the RGB (above the HB), while the less-evolved "unmixed" giants exhibit pristine C and O abundances in their atmospheres.

In Fig. 3 we compare the [C/Fe] ratios of the "unmixed" giants with those in the turnoff stars. A systematic difference of 0.25 dex is seen, which might be the signature of stronger NLTE or 3D effects in giants than in turnoff stars, but no overall trends of [C/Fe] with [Fe/H] are seen. We plan to study this in more detail soon.

Another explanation might be that the first dredge-up has in fact already brought CNO-processed material to the surface of our "unmixed" giants (R. Gratton, priv. comm.). We would then also expect these stars to be more N rich than the turnoff stars. Unfortunately, the abundance of N is even more difficult to measure precisely in EMP turnoff stars than in giants, so we have been unable to test this hypothesis.

Although our sample of turnoff stars was supposed not to contain C-rich stars, a high carbon abundance ($[C/Fe] = +1.2 \pm 0.3$) has been found in one of them: CS29527-15 (Fig. 3). It is also a double-lined binary with a variable Li line (see the paper of Bonifacio *et al.* in this symposium). Later on CS29527-15 has been taken away from our sample of "normal" turnoff stars.

3. Calcium

The [Ca/Fe] ratio has been measured in all four samples of EMP stars, and Fig. 4 shows [Ca/Fe] vs. [Fe/H] for both the turnoff and giant stars. The agreement is excellent, with $< [Ca/Fe] > \simeq +0.35$ in all EMP stars and no trend with [Fe/H].

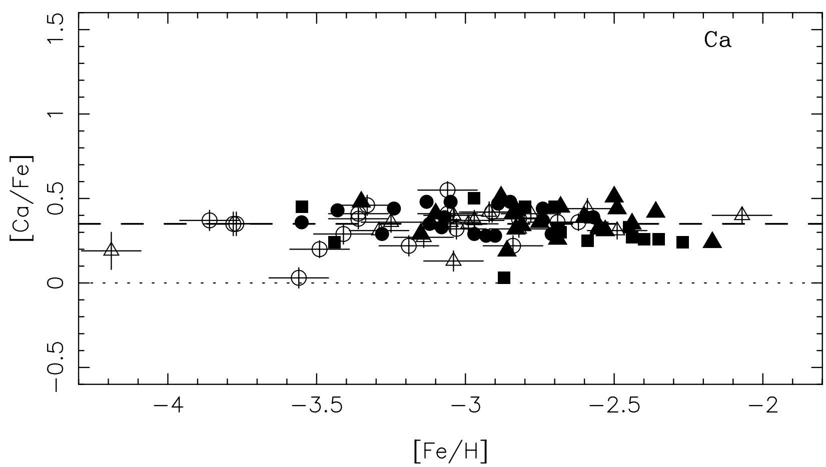

Figure 4. [Ca/Fe] vs. [Fe/H] for the VLT giants (open triangles and circles denote "mixed" and "unmixed" giants, respectively) and all three turnoff samples (filled circles: VLT; filled squares: Keck; filled triangles: AAT). The agreement is excellent, with no trend with [Fe/H].

4. Magnesium

The behaviour of Mg is of special interest, because Mg should be a better reference element for tracing the Galactic chemical evolution than Fe. The early nucleosynthesis of Fe is complex and depends on several uncertain parameters, including the

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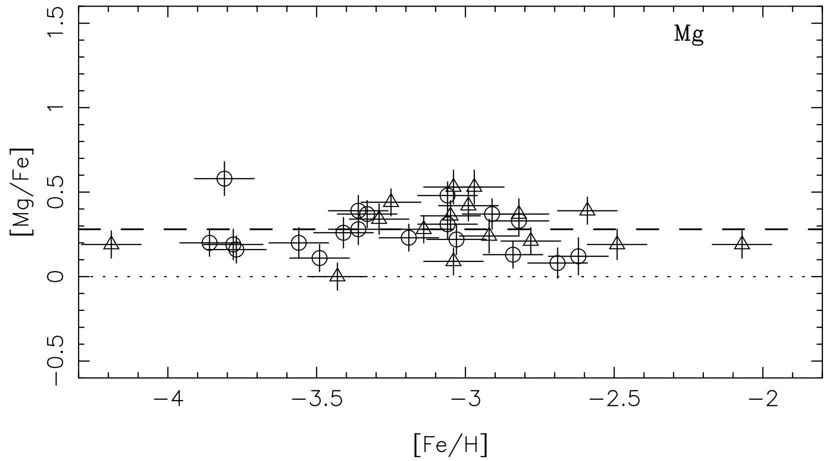

Figure 5. [Mg/Fe] vs. [Fe/H] for the VLT giant sample; open triangles and circles denote "mixed" and "unmixed" stars, respectively.

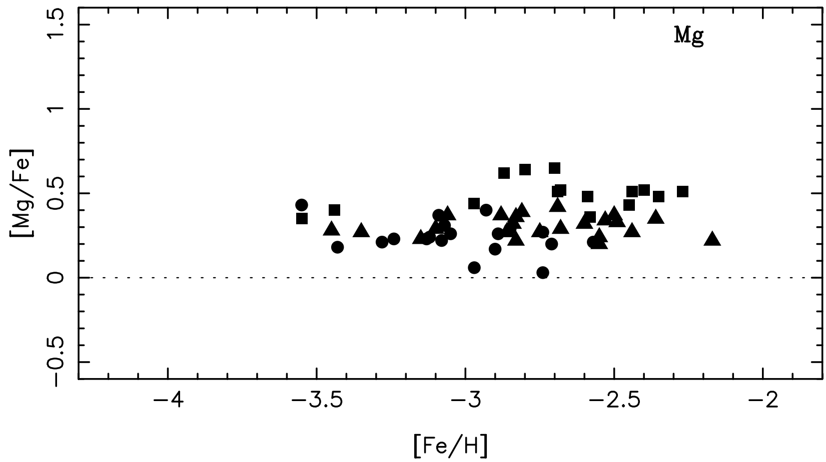

Figure 6. [Mg/Fe] vs. [Fe/H] for the turnoff stars (symbols as in Fig 4). The offsets of $<$ [Mg/Fe] $>$ as measured by the different teams can be due to the uncertain gf values, but within each sample the dispersion is small, below 0.1 dex.

poorly-constrained mass cut in SNe II, but the production of Mg should be free of these complications.

In our study of the RGB stars (Cayrel *et al.* 2004), we found $<$ [Mg/Fe] $> \approx +0.29$ with a standard deviation of $\sigma = 0.14$ dex, rather larger than the expected measurement error of 0.09 dex (Fig. 5). Moreover, the abundance ratios [X/Mg] vs. [Mg/H] showed larger scatter than [X/Fe] vs. [Fe/H], against our initial expectations. It is therefore interesting to compare the results for Mg in the giants and dwarfs to ascertain whether the extra scatter is just due to the smaller number of Mg lines available for measurement, or whether the Mg abundance in giants is affected by as-yet unknown mixing processes.

Like Ca, Mg has been measured in all three turnoff samples; Fig. 6 presents the results. Cohen *et al.* find systematically higher [Mg/Fe] values than Arnone *et al.* and we, but the gf values of the Mg lines are rather uncertain, and results may change significantly depending on the laboratory reference used for each line. Moreover, Cohen *et al.* employ a generally warmer T_{eff} scale than the other studies, which can account for part of the difference. All three turnoff samples show a small dispersion in [Mg/Fe]:

`Cohen  et al. Cohen et al. (2004): [Mg/Fe]=+0.49` $\sigma = 0.09$
`Arnone et al. Arnone et al. (2005): [Mg/Fe]=+0.30` $\sigma = 0.06$
`VLT team (dwarfs) : [Mg/Fe]=+0.22` $\sigma = 0.09$

Thus, the dispersion in [Mg/Fe] appears to be significantly smaller in the turnoff stars than in the giants. Yet, $<$ [Mg/Fe] $>$ as determined in the VLT project (using the same lines and gf values) agrees very well between the giants and turnoff stars, with $<$ [Mg/Fe] $> = +0.28$ for the giant stars and $<$ [Mg/Fe] $> = +0.22$ for the dwarfs. This makes it harder to argue for the presence of extra mixing in the giants; also, Fig. 5 shows no difference between "mixed" and "unmixed" stars. Perhaps the larger volume sampled by the giants includes stars from a greater variety of galactic environments.

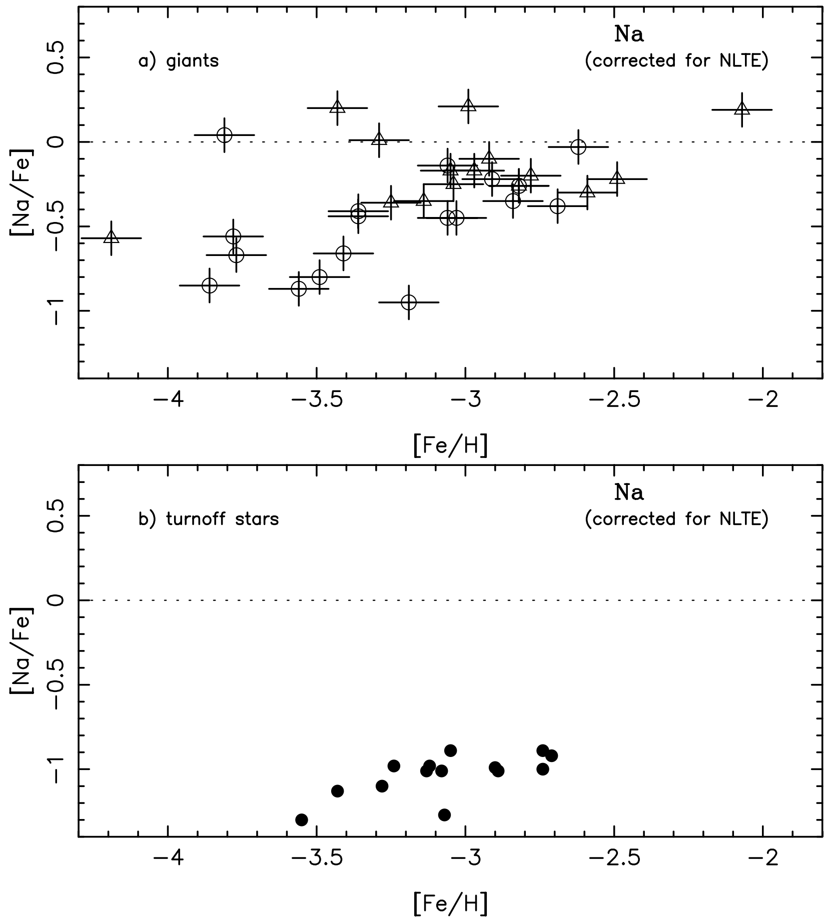

Figure 7. [Na/Fe] vs. [Fe/H] in *a:* the giants (top) and *b:* the turnoff stars (bottom); symbols as in Fig. 4. The scatter is much larger in the giants ($\sigma = 0.27$) than in the turnoff stars ($\sigma = 0.11$, similar to that of the other elements), suggesting the occurrence of deep mixing.

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5. The light odd-Z elements Na and Al

The production of Na and Al is expected to be sensitive to neutron excess. As a consequence, the yields depend on the amount of neutron-rich nuclei present in the supernova at the time of their synthesis. The abundances should depend on metallicity.

In some globular cluster giants, the Na and Al abundances show a large scatter which remains poorly understood up to now. However, in metal-poor field stars ($-2 \leqslant$ [Fe/H] $\leqslant -1$), (Gratton et al 2000), using a variable NLTE correction found no sign of evolution of the [Na/Fe] ratio along the RGB. However, the scatter in [Na/Fe] did seem to be larger in giants than in dwarfs, suggesting the presence of some effect related to evolution.

5.1. *Sodium*

Na abundances have only been measured in our samples, giants as well as turnoff stars. Fig. 7a shows [Na/Fe] vs. [Fe/H] for the giants (both “mixed” and “unmixed”). The scatter is extremely large ($\sigma = 0.27$), with a tendency for the “mixed” stars to be slightly more Na-rich than the “unmixed” stars.

The contrast to the results for the turnoff stars (Fig. 7b) is striking: In the range $-3.4 \leqslant$ [Fe/H] $\leqslant -2.5$, [Na/Fe] is significantly lower than in the giants, and the scatter is also much smaller ($\sigma = 0.11$), strongly suggesting that Na in the giants is affected by internal mixing processes. As a consequence, we expect that the values for the turnoff stars are a better indicator of Na abundance in the early galactic material.

We caution that in EMP stars the Na abundances can be only derived from the resonance lines, which are very sensitive to NLTE effects. We have tried to correct our results for this effect, but actual computations exist only for dwarfs (Baumüller *et al.* 1998). These corrections have been applied in Fig. 7b and lead to $<$ [Na/Fe] $> \approx -1.0$ dex for the turnoff stars.

For the giant stars, we have applied the same NLTE corrections as in the dwarfs, as the best first approximation (Cayrel *et al.* 2004). A more reliable NLTE correction might change the mean value of [Na/Fe] in the giants, but is not expected to change the *scatter* in the relations of [Na/Fe] vs. [Fe/H] significantly, because the corrections would be rather similar for all the stars in Fig. 7a.

Our comparison of Na abundances in EMP dwarfs and giants strongly suggests that Na may sometimes be brought to the surface of the giants by deep mixing. This process has been proposed for globular cluster giants (Denissenkov & VandenBerg 2003), but has not been observed in metal-poor field stars in the metallicity range $-2 \leqslant$ [Fe/H] $\leqslant -1$ (Gratton *et al.* 2000).

5.2. *Aluminium*

Aluminium has been measured in the VLT giant sample and in the VLT and Keck turnoff samples (Cohen *et al.* 2004). All the results are shown in Fig. 8.

There is very good agreement between Al abundances measured in the Keck and VLT turnoff samples; moreover, we find the same Al abundance in the turnoff stars as in the “unmixed” giants.

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VLT team (dwarfs) :          [Al/Fe]=-0.07     σ = 0.08
Cohen  et al. Cohen et al. (2004) (dwarfs): [Al/Fe]=-0.09     σ = 0.11
VLT team (unmix. giants)  :  [Al/Fe]=-0.10     σ = 0.12
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The inferred Al abundance in the early Galaxy is close to $<$ [Al/Fe] $> \approx -0.1$ dex.

However, $<$ [Al/Fe] $>$ is higher in the “mixed” giants than in the “unmixed” giants (assuming that the NLTE correction is good for the giants) and the scatter is larger.

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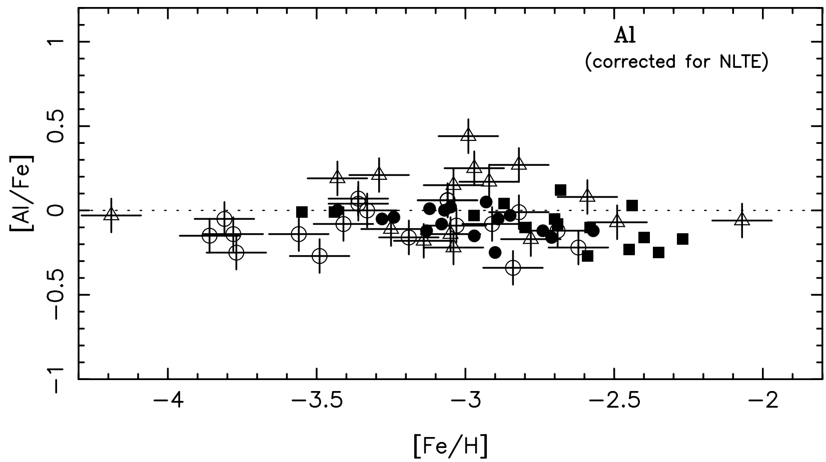

Figure 8. [Al/Fe] vs. [Fe/H] for the giant and turnoff EMP samples (symbols as in Fig. 4). The Al abundances in the turnoff stars and "unmixed" giants agree well, but several "mixed" giants seem to be enriched in Al.

`VLT team (mix. giants) :      [Al/Fe]=+0.06` $\sigma = 0.19$

We conclude that the "mixed" (lower-gravity) giants may sometimes (but not always) bring Al to the surface by deep mixing. However, the effect is much smaller than for Na, and a "Na-rich" star is not always also "Al-rich".

6. Conclusions

This study has led to two major conclusions: First, when allowing for possible differences in the adopted gf values, the recent independent abundance studies for EMP turnoff stars are in excellent agreement. Second, the different abundance patterns for some elements between turnoff and giant stars, notably C and Na but to a lesser extent also Al and Mg, suggest that the atmospheres of some giant stars are polluted by products of the complete CNO cycle. This may occur even for stars on the lower part of the RGB (tentatively called "unmixed" giants by Spite *et al.* (2005)).

The search for the explanation of these observations may lead to new insight in either Galactic evolution or stellar physics, or both. On the one hand, recent analyses of stars in nearby dwarf galaxies reveal variations in [α/Fe], which could lead to increased scatter in [Mg/Fe] dues to accreted objects in the giant sample. On the other hand, an increased scatter in the surface abundance of certain elements, but no net enrichment (e.g. for Mg), if confirmed, might point to the existence of more subtle circulation mechanisms in stars. Both avenues are worth pursuing.

Acknowledgements

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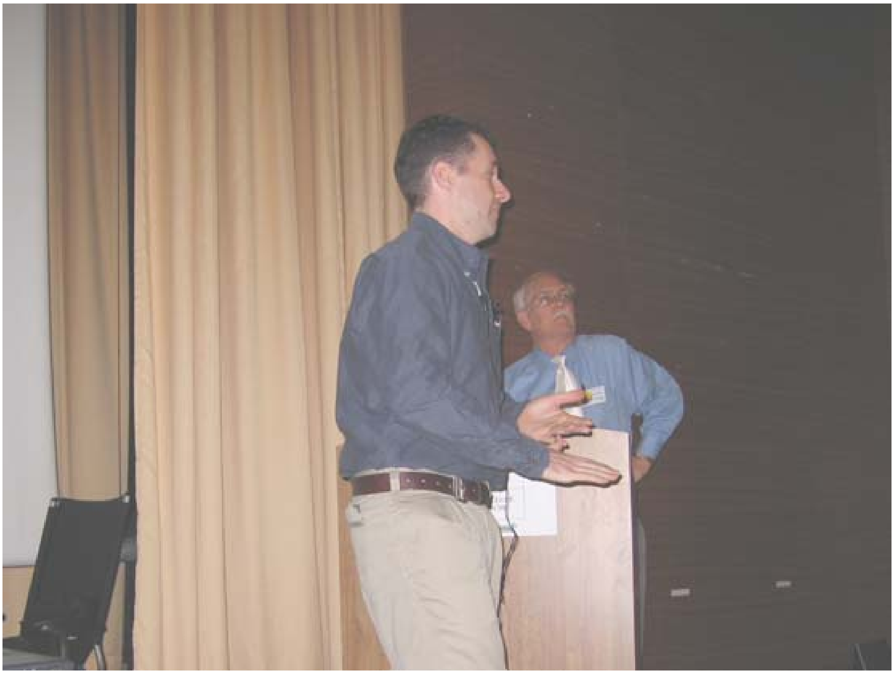

Paul Barklem explaining his automated abundance analysis of a very large sample of metal-poor stars (HERES).

Thomas Masseron, presenting abundances in carbon-rich stars.

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