The Galaxy Disk in Cosmological Context
Proceedings IAU Symposium No. 254, 2008
J. Andersen, J. Bland-Hawthorn & B. Nordström, eds.

doi:10.1017/S1743921308027804

Halo chemistry and first stars. The chemical composition of the matter in the early Galaxy, from C to Mg †

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Abstract. From NLTE computations of the magnesium abundance in a sample of extremely metal-poor giants we derive [Mg/Fe]=+0.7, leading to [Al/Mg]=–0.80 and [Na/Mg]=–0.85 in the early Galaxy. The ratio [O/Mg] should be near to the solar value. Measurements of nitrogen abundances derived from the analysis of the NH band in eight more stars confirm the large scatter of the ratios [N/Fe] and [N/O] in the early Galaxy.

Keywords. Stars: abundances, stars: atmospheres, stars: Populations II, Galaxy:abundances, Galaxy:evolution, nucleosynthesis

1. Introduction

The "Extremely metal-poor" stars formed less than 1 Gyr after the formation of the Galaxy. They are extremely metal-poor because, at that time, the matter had been enriched by a very small number of supernovae. Moreover, these first supernovae could only be massive type II supernovae which have a very short lifetime.

In contrast, the chemical composition in the Galactic disk is the result of enrichment not only by SNII, but also by AGB stars and SNI.

Seven years ago, to take advantage of the high-resolution spectrograph UVES at the VLT, and of the existence of a large sample of EMP stars (H&K survey: Beers, Preston & Schectman 1992), Roger Cayrel stimulated the formation of a "First stars team" to apply for an ESO Large Program dedicated to the study of the chemical composition of the Galactic matter in the early times. Other teams in the world have chosen to work on similar subjects, in particular at the Keck and SUBARU telescopes in Hawaii or at

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† Based on observations made with the ESO Very Large Telescope at Paranal Observatory, (Large Programme "First Stars", ID 165.N-0276; P.I.: R. Cayrel, and Programme 078.B-0238; P.I.: M. Spite).

the AAT in Australia. Generally speaking, there is a rather good agreement between the results of these different teams.

2. Observations and Spectrum analysis

In summary, 52 very metal-poor stars (34 with [Fe/H] < -2.9) were observed in the "First Stars" programme (S/N $\approx$ 200, R $\approx$ 45000, $3350 < \lambda < 10000$). All these stars were "normal" metal-poor stars, not carbon-enriched, but some carbon-rich stars were observed for comparison. Later in a complementary run focused on the problem of the nitrogen abundance, ten more giant stars in the lower part of the HR diagram were observed in the same conditions.

In a first step, a classical LTE analysis was performed using MARCS theoretical 1D plane-parallel model atmospheres (Gustafsson *et al.* 2008). The stellar effective temperature was determined from photometry (or the wings of the Hα line, for dwarfs) and the gravity from the ionization equilibrium of iron.

More details can be found in Cayrel *et al.* (2004) and Bonifacio *et al.* (2007, 2008).

3. [O/Mg], [Na/Mg] and [Al/Mg] in the Galaxy, Influence of NLTE effects.

In extremely metal-poor stars, the lines are often very weak and the abundance of several elements like sodium or aluminum can be determined only from the resonance lines. However, it is well known that these lines are very sensitive to NLTE effects. As a first approximation we applied a systematic non-LTE correction actually estimated for dwarfs to all the stars (Cayrel *et al.* 2004). But in both cases the scatter in the abundance ratios was very large; for Na there was strong disagreement between dwarfs and giants. After a complete NLTE computation of the Na and Al resonance lines, the agreement between the Na and Al abundances in giants and in dwarfs became very good and the scatter much smaller (Andrievsky *et al.* 2007, 2008).

But as noted by Gehren *et al.* (2006) non-LTE effects are also not negligible when computing Mg abundances in metal-poor stars. Therefore we decided to compute also NLTE profiles for Mg lines. For giants we found a mean NLTE correction of about +0.4 dex and [Mg/Fe] $\approx +0.7$ (computations for dwarfs are in progress). In Cayrel *et al.* (2004) we measured [O/Fe] $\approx +0.7$ (without 3D correction). This measurement of the oxygen abundance is not sensitive to NLTE effects (forbidden line). The new value of the magnesium abundance in giants would imply [O/Mg] $\approx +0.0$ in the early Galaxy.

In figures 1 and 2 we show the variation of the ratios [Al/Mg] and [Na/Mg] in the Galaxy. For the disk stars [Al/Mg] is larger than –0.1dex (Gehren, 2006), in the halo this ratio decreases, the minimum is reached at about [Fe/H]=–3.0 with [Al/Mg] $= -0.8$, then at lower metallicity it seems to increase slightly.

At very low metallicity the scatter of [Na/Mg] is larger than for [Al/Mg], but all the "Na-rich" stars are "mixed" stars. These stars have a high N abundance coupled with a low C abundance and a low value of the $^{12}C/^{13}C$, ratio, indicating a mixing with the H burning layer. If this mixing is particularly deep, it can bring products of the O, Ne, Na cycle to the surface (Denissenkov & Pinsonneault 2008). The relation between [Na/Mg] and [Fe/H] is a continuous enrichment through all three galactic populations, halo, thick disk, thin disk. The minimum is reached at about [Fe/H]=–3.0 with [Na/Mg] ≈ -0.85, then at lower metallicity it is possible that [Na/Mg] increases slightly.

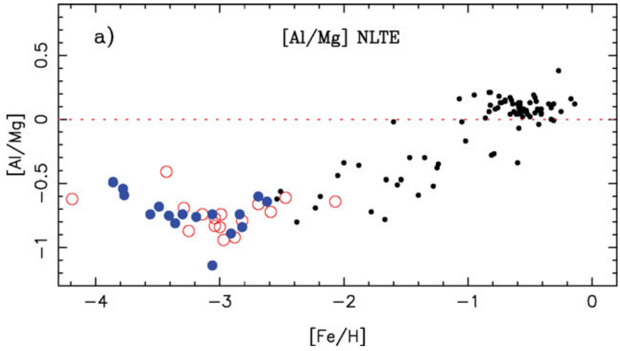

Figure 1. Evolution of the [Al/Mg] ratio in the Galaxy as a function of [Fe/H]. The small black dots are the data by Gehren *et al.* (2004, 2006) for the disk and the halo. The large blue dots represent our sample of "unmixed" giants, the open circles the "mixed" giants.

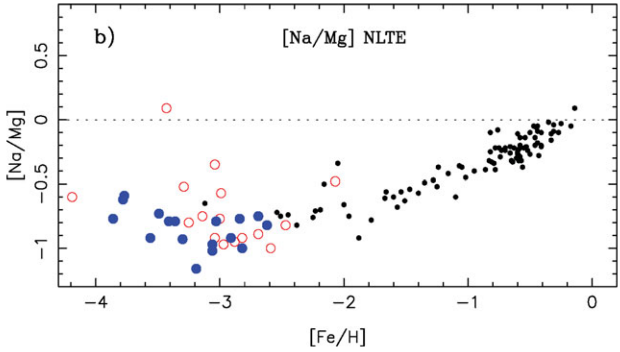

Figure 2. Same as Fig. 1, but for [Na/Fe]. At very low metallicity the scatter is larger than for [Al/Mg] but all the "Na-rich" stars are mixed stars, and the enrichment is probably due to mixing with the deep H burning layer.

4. C and N abundances in the early Galaxy

In extremely metal-poor stars, carbon and nitrogen abundances are derived from the G band of CH (430 nm) and the violet band of NH (336 nm). In general, the NH (and CN) bands are not visible in the spectra of EMP turnoff stars (the stars are too hot), so the N abundance can be determined only in giants. On the other hand, the abundances of C and N in the pristine gas can be deduced only from stars located below the bump in the HR diagram. At higher luminosity, the atmospheres of the stars are significantly altered by mixing and thus are not a good diagnostic of the initial chemical composition (Spite *et al.*, 2005, 2006).

In Spite *et al.* (2005), we showed from our sample of unmixed stars that the N abundance in the early Galaxy showed large scatter. But since there were only few unmixed giants, we could not decide between a simple scatter, two different levels of abundance, or even an anti-correlation between [Fe/H] and the [N/Fe] or [N/Mg] ratios.

We have recently observed the region of the NH band in eight more "unmixed" EMP giants, selected from the sample of Barklem *et al.* (2005). The N abundances in these stars have been computed from synthetic spectra. The results are shown in Fig. 3. These new measurements support the existence of significant scatter in [N/Fe] in EMP stars. This scatter could reflect different rotational velocities in the massive first stars (e.g. Meynet *et al.*, 2008). The scatter seems to be even smaller at very lowest metallicities.

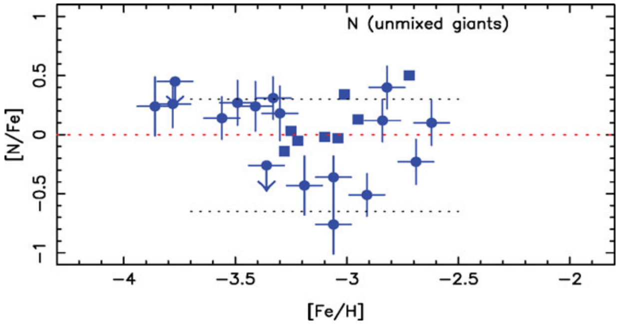

Figure 3. [N/Fe] in EMP giants. Our new measurements are shown as squares.

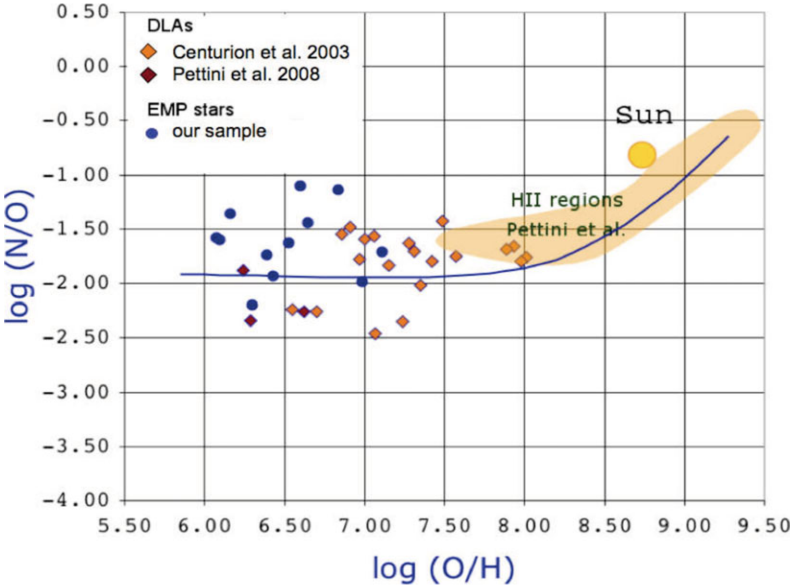

Figure 4. log N/O for H2 regions, DLAs (diamonds) and EMP stars (blue dots)

However, for [Fe/H] < -3.4 the NH band is only measurable if [N/Fe] > 0, so the smaller scatter in this domain could be a spurious effect.

In three of the newly observed stars it was possible to measure the oxygen abundance from the forbidden O I line (see Cayrel *et al.* 2004). These measurements are in good agreement with the previous measures.

For all the EMP stars with measured N and O abundances, the ratio N/O can be compared to the values obtained in DLAs by Centurion *et al.* 2003, or Pettini *et al.* 2008 (Fig. 4). At low metallicity the scatter of the ratio N/O is large in both stars and DLAs. There is no indication of a decrease of N/O with O/H as it would be expected if the formation of N would depend on the metallicity of the progenitor. In fact, the mean N/O ratio remains almost constant. Massive stars may contribute significantly to the nucleosynthesis of O, but also of C and N (Meynet *et al.*, 2008).

5. Conclusions

Precise computations of the abundances of the light metals Na, Al and Mg in extremely metal-poor stars have shown that it is important to take NLTE effects into account. From our preliminary NLTE computations of the Mg abundance in EMP giant stars, we found that: [Mg/Fe] $\approx +0.7$dex, [Al/Mg] ≈ -0.80dex and [Na/Mg] ≈ -0.85dex.

We note that all the ratios [X/Mg] in Cayrel *et al.* (2004) would have to be corrected in the same way, and in particular, the mean value of [O/Mg] at very low metallicity could be close to the solar value.

New observations of a sample of "unmixed" metal-poor giants confirm the large scatter of the ratios N/O and N/Fe. The mean value of N/O is almost constant in the interval $6 < \log(O/H) < 7.5$.

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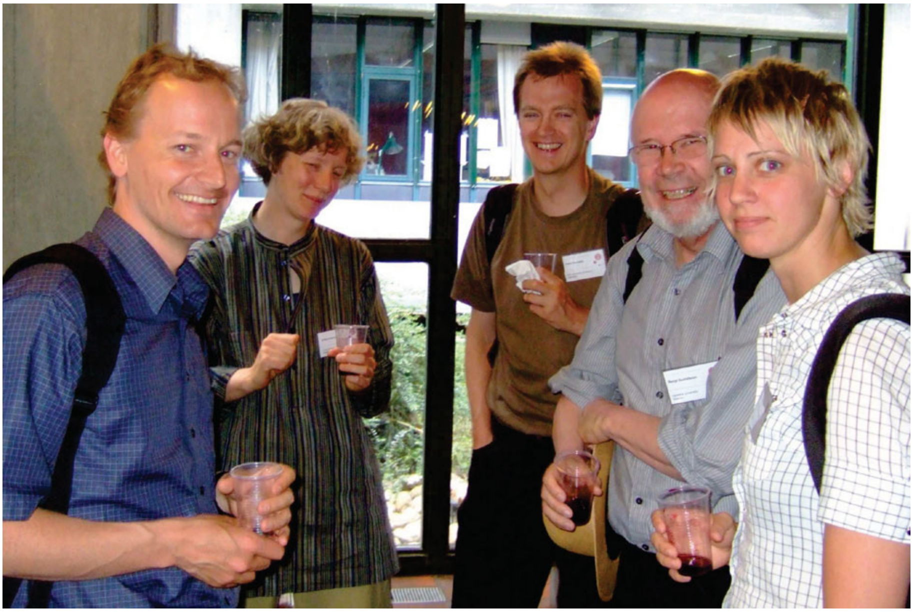

A stellar abundance gang relaxing outside the lecture hall: Andreas Korn, Sofia Feltzing, Frank Grundahl, Bengt Gustafsson, and Anna Önehag.

Preben Grosbøl, Carme Jordi, and Claus Fabricius at Carlsberg.