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Trends of Abundance in Extremely Metal-poor Giants Observed at the VLT

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Abstract
We present here the first abundance trends from C to Zn deduced from the observation of 33 extremely metal-poor stars selected in the HK survey of Beers et al. (1992). The trends of the abundance ratios of the different elements like [Mg/Fe], [Cr/Fe] are not very different from the trends deduced from the observations of McWilliam et al.(1995), but for several important elements (like Mg, Cr) the spread is much smaller. For almost all the elements the spread increases when the metallicity decreases, this is particularly evident for the trend of [Mn/Fe] versus [Fe/H].
The elements heavier than Zn will be discussed later.

1.1 The ESO Large Program "First Stars, First Nucleosynthesis"

The chemical composition of the atmosphere of the extremely metal-poor Galactic stars (XMP stars) contains unique information on the earliest epoch of star formation and nucleosynthesis in our Galaxy. But in general these stars are rather faint, and up to recently, the accuracy of the results was limited by the resolution and the S/N ratio of the spectra obtained with 4m-class telescopes. As a consequence we have conducted a large program at the ESO Very Large Telescope (VLT) and its UVES spectrograph to obtain a systematic, homogeneous spectroscopic analysis of a large sample of extreme halo stars selected from the HK survey of Beers et al. (1992) and Beers et al. (1999).

The PI of the program is Roger Cayrel and it involves 13 coI's from different institutes. The aim of this project was to explore :

- The nature and ejecta of the first supernovae
- The efficiency of mixing processes in the early Galaxy
- The age of the Galaxy (and Universe) via stellar chronometers, thorium and uranium. (cf. the talk of Roger Cayrel in this symposium)

There are different approaches to these problems : for a given observing time you can observe either
-a large sample of XMP stars with a moderate S/N ratio in a small wavelength range or

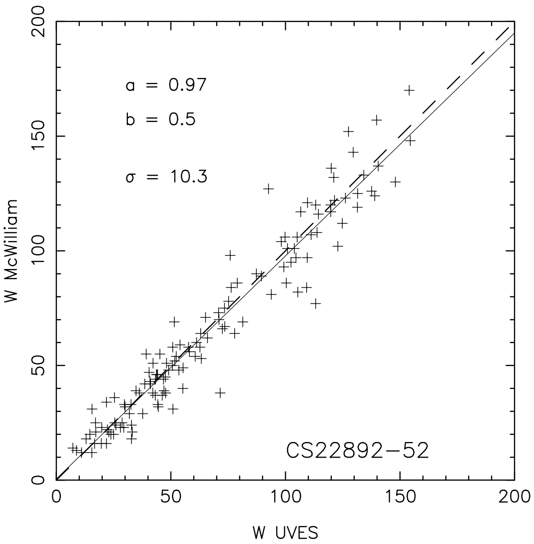

Fig. 1.1. Comparison between our EWs and those of McWilliam et al.(1995). The one to one relation is represented by a dashed line and the mean curve (least squares) as a full line. The value of the slope (a) and of the zero point shift (b) of the regression are given as well as the standard deviation (σ). The spread is due to the lower resolution and S/N of the spectra of McWilliam

-a relatively small (but "significant") number of XMP stars with a high S/N ratio and in a large range of wavelength.

Since, in these XMP stars the lines are often extremely weak (less than 3mÅ) and that we want to analyze a large number of elements, we have chosen the second option.

1.2 Observations and Reductions

Thirty eight nights at the VLT with the high resolution spectrograph UVES were devoted to this program between April 2000 and November 2001. We could observe about 40 giants and 30 dwarfs. This talk concerns only the giant stars. The resolution of the spectra is 45000 and the spectral coverage is almost complete between 330nm and 1000nm. Most of the stars (29 out of 33) have a metallicity [Fe/H]$<$ -2.7. The S/N of the spectra is generally between 100 and 200 per pixel at 500nm. But since there are 7 pixels per element of resolution this value has to be multiplied by about 2.5 to obtain the S/N ratio by element of resolution.

The spectra were reduced using the UVES package within MIDAS (bias and inter-order background subtraction, optimal extraction of the object above sky, division by a flat-field, wavelength calibration, and merging of all overlapping orders). The different spectra of a same star were then coadded and normalized to unity in the continuum. The equivalent widths have been measured by gaussian fitting.

In Fig.1.1 we compare our equivalent widths to the equivalent widths measured by McWilliam (1995). The spread is rather large because the resolution and the S/N ratio of the spectra of McWilliam is much lower (R=22000, S/N$\approx$ 40).

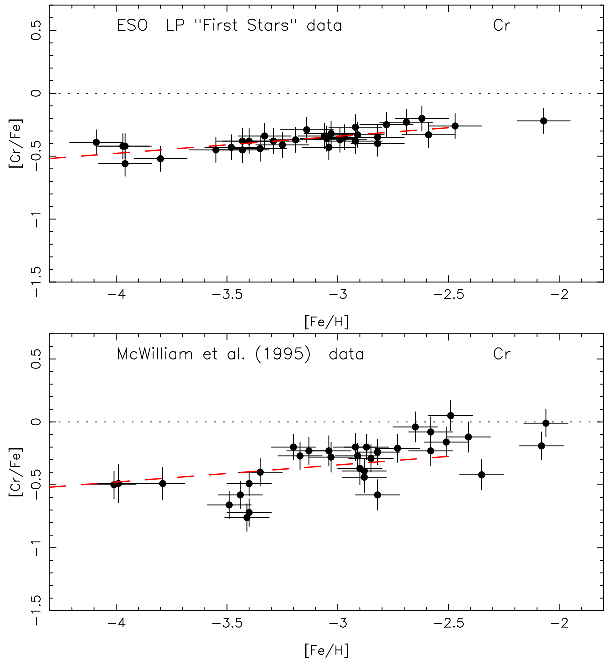

Fig. 1.2. Comparison between the relation [Cr/Fe] versus [Fe/H] obtained from our high precision measurements and the relation obtained by McWilliam et al. (1995). On the figures the regression line (dashed line) has been computed from our measurements but it is compatible with the measurements of McWilliam. The dispersion of our measurements is much smaller (σ=0.05) and it may be explained by the measurement errors only.

When our equivalent widths are compared with equivalent widths measured on spectra with higher resolution and S/N, the spread is much smaller: it is only 3.6 mÅ when compared to Johnson (2002) and even lower (2 mÅ) if the comparison is restricted to lines weaker than 30mÅ.

1.3 Analysis

The abundance analysis was performed with the LTE spectral line analysis code "turbospectrum" associated with OSMARCS models. The OSMARCS models were originally developed by Gustafsson et al. (1975) and improved through the years by Plez et al. (1992), Edvardsson et al. (1993) and Asplund et al. (1997). The spectral synthesis program "turbospectrum" is described in Alvarez & Plez (1998) and has been recently improved, partly for this work.

The temperature of the stars was estimated from the color indices (B-V), (V-R), (J-K), (V-K) and (V-I) using Alonso's calibration for giants (Alonso et al. 1999) and the gravity was deduced from the ionization equilibrium of Ti and Fe. The largest uncertainties in the abundance determination arises from the uncertainty in the temperature of the stars. If we assumed in a conservative way, that this error is about 150K then the error in [Fe/H] is about 0.15 dex and the error in [Ti/Fe] [Al/Fe]... is less than 0.10 dex.

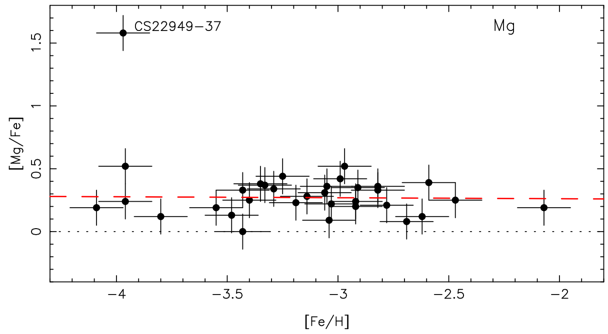

Fig. 1.3. [Mg/Fe] plotted vs [Fe/H] (σ observed = 0.13, σ expected from measurement errors only = 0.11)

1.4 Trends and Dispersions from C to Zn

The abundances of the elements from C to Zn have been determined for all the stars of the sample and for each element X we have plotted the ratio [X/Fe] versus [Fe/H] in the interval $-4. < [\mathrm{Fe/H}] < -2.5$.

For the elements we have in common, there is a rather good agreement with the trends found by McWilliam et al. (1995) but the dispersion in our measurements is much smaller. As an example we compare in Fig.1.2 the relation [Cr/Fe] versus [Fe/H] to the relation obtained by McWilliam. On both figures the dashed line is the regression line computed from our measurements. It can be seen that it is also compatible with the measurements of McWilliam. However the dispersion around the regression line is not always very small. Chromium is our best example. In this case the scatter (0.05) is independent of the metallicity (in the interval $-4. < [\mathrm{Fe/H}] < -2.5$) and can be explained by measurement errors only. In case of magnesium (Fig.1.3) the dispersion is a little larger but the ratio [Mg/Fe] is more sensitive to an error of temperature than the ratio [Cr/Fe] and thus the dispersion of [Mg/Fe] can be also explained by measurement errors only.

Generally the dispersion increases when the metallicity decreases (cf. in particular in the next section the relation [Mn/Fe] versus [Fe/H]).

1.4.1 The Iron-peak Elements

It is interesting to compare (Fig.1.4) the behavior of the iron peak elements built by the complete explosive silicon burning (Co, Zn) and the elements built by the incomplete silicon burning (Cr, Mn).

It seems difficult to explain with standard models that the abundances of Cr and Mn decrease when Co and Zn increase. Umeda and Nomoto (2002) suppose that at a [Fe/H]= -4.0 the main contributors to the metal-enrichment of the interstellar medium are massive supernovae with masses around $25M_{\odot}$, whereas at -3.0 the masses of the progenitors would include SN II down to masses around $13M_{\odot}$. Therefore they assume that the explosion energy is higher and the mass cut deeper in the more massive supernovae. As a consequence more products of complete silicon burning would be ejected at low metallicity in the more massive supernovae.
The enhancement of Zn at low metallicities excludes the very massive pair instability SN as the first supernovae.

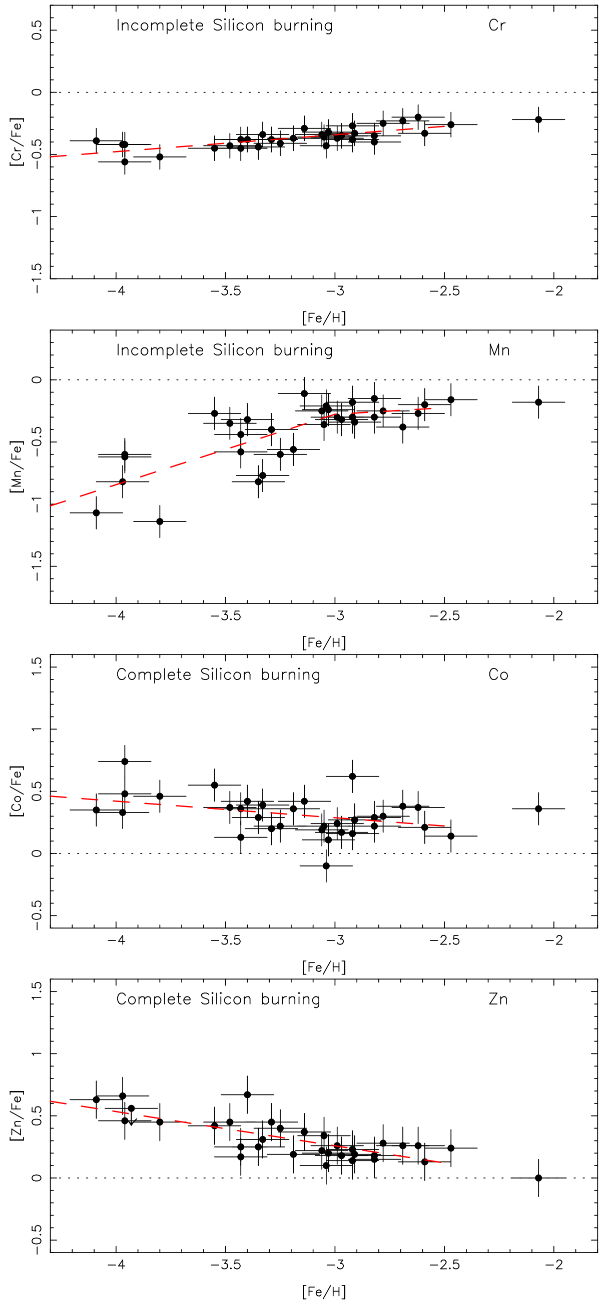

Fig. 1.4. The abundance of Cr and Mn (relative to iron) decreases when the metallicity decreases but the abundance of Co and Zn increases.

Let us remark that Zn is used to determine the mean metallicity of Damped Ly$_\alpha$ systems (DLA) because, at variance with iron, it is not locked on the dust. If at low metallicity

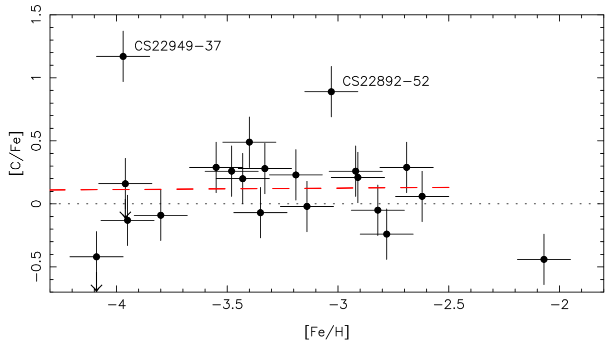

Fig. 1.5. [C/Fe] versus [Fe/H] for the stars of our sample with temperature higher than 4800K (to avoid mixing with deep layers where carbon is transformed into nitrogen). [C/Fe] is close to zero but the stars of our sample have been selected with "no-strong" G-band, (except for CS22892-52 and CS22949-37) and thus this sample is severely biased. The two CH rich stars of the sample have not been taken into account for the computation of the regression line (dashed line)

[Zn/Fe] is positive then the most metal-poor DLA's are more metal poor than expected and their content in dust is lower.

1.4.2 Carbon and Oxygen

The carbon abundance has been determined by fitting the computed CH rotation-vibration band at 422.4nm to the observed spectrum.

Among very metal-poor stars it has been found that about 25% of the stars are carbon-rich (Rossi et al., 1999), but in our sample we have selected stars without "strong" G-band, except for CS22892-52 (Sneden et al., 1996, 2000) and CS22949-37 (Depagne et al., 2002). As a consequence this sample is severely biased and cannot be used to constrain the scatter in [C/Fe] at low metallicity.

In Fig.1.5 we present the relation [C/Fe] versus metallicity for the stars of the sample with a temperature higher than 4800K. At lower temperature a mixing with deep layers where carbon is converted into nitrogen occurs, and the mean carbon abundance decreases with the temperature (Langer et al. 1986, Kraft 1994). In this sample we found that [C/Fe] is close to zero. We even cannot exclude that below [Fe/H] =-3.5, the ratio [C/Fe] decreases with the metallicity but more observations would be necessary.

The oxygen abundance has been determined from the forbidden [OI] line at 630.03nm. It is generally admitted that this line is not sensitive to non-LTE effects and is the most reliable (Kraft 2001, Kiselman 2001, Nissen et al. 2002). Unfortunately it is very faint in XMP stars and it can be measured only if it is not superimposed to a strong telluric line in emission or in absorption. We have computed the oxygen abundance with OSMARC 1D model and we adopted log gf = −9.72 and $\log\epsilon_{\odot}$ = 8.74 (Allende Prieto et al. 2001). With these values we found that in the interval $-3.5 < [\mathrm{Fe/H}] < -2.5$ the abundance of oxygen is practically constant and close to [O/Fe]=0.7 (Fig.1.6).

Let us remark that the extremely metal-poor star CS 22949-037 has an exceptionally

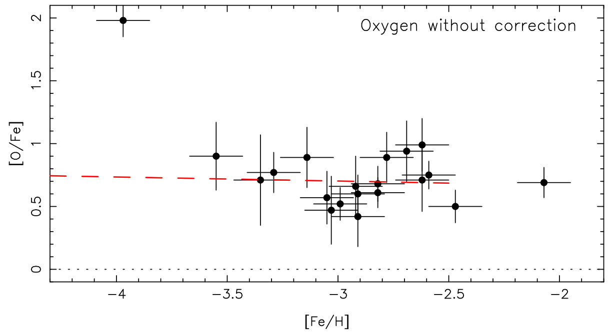

Fig. 1.6. [O/Fe] plotted vs [Fe/H]. The slope of the regression line (dashed) is not significant. The level of the plateau is at about +0.7. The star at [Fe/H]=-4 is CS 22949-37. This star is very peculiar: all the light elements between C and Si are very strong. The oxygen line is not visible in any other star with a metallicity close to -4 as expected if the ratio [O/Fe] is also close to 0.7 for these stars.

high O abundance which has been discussed in Depagne et al. (2002). But this star is very peculiar, it has also a very high abundance of magnesium and it is not representative of the metal-poor stars with [Fe/H]=–4.0. In none of the other stars of our sample with [Fe/H]< -3.8, is the forbidden oxygen line detected, and the upper limits implied by this non-detection are of the order of $[\mathrm{O/Fe}] \leq 1.0$dex.

We computed indeed that, if these stars have the same ratio [O/Fe]=0.7 than the other XMP stars then, the expected equivalent widths would be less than 0.5mÅ, a value which is generally lower than our detection limit in this region of the spectrum.

It has been noted that the ratio [O/Fe] in metal-poor stars is different if 3-D models are used. A correction 1D – 3D has been computed for dwarf metal-poor stars (Nissen et al., 2002) but not for giants. However Nissen et al. note that the sign of the correction is unlikely to change and that therefore the [O/Fe] ratio based on [OI] lines should always become smaller in 3D than in 1D. If we apply to our stars the correction computed for dwarfs, we found that [O/Fe] $\approx$ +0.5 in the interval $-3.5 < [\mathrm{Fe/H}] < -2.5$.

A detailed presentation and discussion of these results will be shortly published in A&A (Cayrel et al. 2003).

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