LOW METALLICITY STARS IN OUR GALAXY

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\textbf{Abstract.} The advent of 8 m class telescopes has allowed the detailed spectroscopic study of sizeable numbers of extremely metal-poor Galactic stars which are the witnesses of the formation of the early Galaxy. Their chemical composition displays some distinctive trends which should provide a strong constraint on the physical nature of the first generation(s) of stars and on their nucleosynthetic output. I will review recent results in the field following the periodic table, from lithium to uranium and shortly comment on the intriguing classes of Carbon Enhanced Metal Poor (CEMP) stars, for many of which there is no analogue among solar metallicity stars. In spite of these exciting results, the number of known stars of metallicity below [Fe/H]=-3.3 remains quite small and it would be desirable to discover more, both to clearly understand the metal-weak tail of Halo metallicity distribution and to clarify the abundance trends at the lowest metallicities. Most of these extremely rare objects have been discovered by the wide field objective prism surveys, HK survey and Hamburg-ESO survey. In the near future the Sloan Digital Sky Survey and its continuation SEGUE are expected to boost significantly the numbers of known extremely metal poor stars. We are living exciting times but an even more exciting future lies ahead!

1 Introduction

In this review I will try to outline the observational picture of the chemical composition of extremely metal-poor stars as it emerges from recent investigations. I will not dwell on interpretations of the chemical patterns, since this topic will be covered by other speakers at this conference.

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Lithium

Lithium is the heaviest of the nuclei produced primordially in the first three minutes of the existence of the Universe and the lightest of the “metals”, in the astronomical acception of the term. Since, over 20 years ago, Monique and François Spite discovered that warm metal-poor stars share the same lithium abundance (the so-called Spite plateau), and interpreted this as the lithium primordially produced (Spite & Spite 1982a, 1982b), a very active research has been carried out in the field. The major challenge to the interpretation of the Spite plateau as evidence for a primordial production of lithium comes from the value of $\eta$ (the baryon to photon ratio) inferred from the fluctuations of the Cosmic Microwave Background, as measured by the WMAP satellite (Spergel et al. 2003, 2006). When used in Standard Big Bang Nucleosynthesis computations, this value implies $A(\text{Li}) = 2.64$. The highest values claimed for the Spite plateau (Bonifacio et al. 2002; Meléndez & Ramírez 2004) are about 0.3 dex lower; many other recent claims are even lower (see Bonifacio et al. 2006, and references therein). This has also been called the “cosmological lithium discrepancy” (Korn et al. 2006).

To complete the observational picture one should add that some investigations suggest a slope in Li abundance vs. [Fe/H] of about 0.1–0.2 dex/dex (Ryan et al. 1996a, 1999; Boesgaard et al. 2005; Asplund et al. 2006), while other investigations fail to detect any slope (Spite et al. 1996; Bonifacio & Molaro 1997; Bonifacio et al. 2002, Meléndez & Ramírez 2004) or find a very shallow one (Charbonnel & Primas 2005). The presence of such a slope clearly does not allow to interpret the Spite plateau as primordial lithium.

Finally an exciting result is the measurement of $^6\text{Li}$ in metal-poor stars, although the interpretation of these measurements is by no means straightforward. A non-controversial measurement of $^6\text{Li}$ was achieved in the 1990’s for only one halo star: HD 84937 (Smith et al. 1993; Hobbs & Thorburn 1994; Smith et al. 1998; Cayrel et al. 1999), with $^6\text{Li}/^7\text{Li} \sim 5\%$. Subsequently, measurements of $^6\text{Li}$ have been claimed for three other halo stars, but have been withdrawn on the basis of higher quality spectra. Smith et al. (1998) measured $^6\text{Li}$ in BD +26°3578 (= HD 338529), but Asplund et al. (2006) changed this to an upper limit. Deliyannis & Ryan (2000) measured $^6\text{Li}$ in HD 140283 but Aoki et al. (2001) changed this to an upper limit. Nissen et al. (2000) measured $^6\text{Li}$ in G 271-162, and also for this star Asplund et al. (2006) changed it to an upper limit. The investigation of Asplund et al. (2006) lead to the measurement of $^6\text{Li}$ in nine more halo stars. All the 10 stars with $^6\text{Li}$ measurements have the same Li isotopic ratio $^6\text{Li}/^7\text{Li} \sim 5\%$; we are therefore in presence of a $^6\text{Li}$ plateau which mirrors the $^7\text{Li}$ plateau.

Korn et al. (2006) have measured Li and Fe in stars of different luminosity.
in the globular cluster NGC 6397 and found lower Fe and Li abundances in the Turn-Off stars than in the sub-giant stars. They argue that this is a result of atomic diffusion in the atmospheres of these stars and claim that this could “solve” the cosmological lithium problem. This work is extremely suggestive, however it should be noted that this result is at odds with previous analysis of this same cluster (Castilho et al. 2000; Gratton et al. 2001), and relies in a crucial way on the temperature scale adopted, in particular on the effective temperature assigned to the TO stars. An increase of 100 K of the assumed TO temperature would effectively erase the abundance differences found.

3 Beryllium

The only production channel for Be is cosmic ray spallation: either fast C, N and O nuclei hit H and He in the interstellar medium (ISM), or fast protons and α particles hit C, N or O nuclei in the ISM. Whichever the case, light nuclei ⁶Li, ⁷Li, ⁹Be, ¹⁰B and ¹¹B are produced. It has been known for over 20 years that metal-poor stars show low Be abundances (Molaro & Beckman 1984) and that there is a linear rise of Be abundance with metallicity (Gilmore et al. 1992; Ryan et al. 1992; Molaro et al. 1997; Boesgaard et al. 1999b; Boesgaard & Novicki 2006). This well established trend, and the simplicity of the Be production mechanism, suggested its possible use as a chronometer (Beers et al. 2000; Suzuki et al. 2001). The measurement of Be in two Globular Clusters, NGC 6397 (Pasquini et al. 2004) and NGC 6752 (Pasquini et al. 2006), and the good agreement between the “Be ages” and the ages derived from Main Sequence fitting, demonstrated the usefulness of Be as a chronometer. Furthermore Pasquini et al. (2005) were able to show that, independently of the absolute calibration of the “Be age”, Be abundances can be usefully used as a “time-like” axis to study the evolution of other abundance ratios, allowing to discriminate the various Galactic populations (e.g. Halo vs. Thick Disc).

Beryllium measurements rely on the 313 nm Be ¹I resonance doublet, quite near to the atmospheric cut-off, and are always observationally challenging. Our ability to fully exploit the chronometric opportunities of this element in the future, will depend on the existence of high resolution spectrographs, efficient in the near UV, on large or extremely large telescopes.

4 Carbon and Nitrogen

At the lowest metallicities our knowledge of these two elements, is mainly due to giant stars in which molecular lines of CH, CN, NH can be measured down to very low metallicities. This poses immediately a problem: the abundances of these elements in the atmospheres of giants may be altered due to mixing episodes. Luckily both the Li abundances and the combined C and N abundances can be used to discriminate observationally between “mixed” and “unmixed” giants (Spite et al. 2005). In fact examination of the isotopic ratio ¹²C/¹³C, allows to conclude that
Fig. 1. Recent measurements of oxygen in metal poor stars, based only on the [OI] 630 nm forbidden line: unmixed giants from Cayrel et al. (2004, filled hexagons), mixed giants from Cayrel et al. (asterisks), subgiants from García Pérez et al. (2006, open squares), main sequence and subgiant stars from Nissen et al. (2002). The dotted line shows the Pop II plateau claimed by García Pérez et al., while the solid line is a simple linear regression to the available data. The [Fe/H] values of Nissen et al. and García Pérez et al. have been shifted by −0.2 dex, in order to be on the same scale of the data of Cayrel et al., as described in Bonifacio et al. (2006). The [O/Fe] values, instead, have not been altered, since for all the authors they reflect [O/FeII], which is not overly sensitive to errors in surface gravity.

The mixing in luminous RGB stars is more extensive than predicted in “standard” models (Spite et al. 2006).

The “unmixed” giants can be used as reliable tracers of the Galactic chemical
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5 Evolution. Looking only at “unmixed” giants one finds that the \([\text{C/Fe}]\) and \([\text{C/Mg}]\) ratios are constant with metallicity, or in other words, carbon tracks iron and magnesium. Also for nitrogen one finds that \([\text{N/Fe}]\) and \([\text{N/Mg}]\) are constant with metallicity, at least for \([\text{Mg/H}] \leq -1.4\), at higher metallicities the \([\text{N/Mg}]\) rises from the value of \(\sim -0.8\) up to the solar value (Spite et al. 2005; Israelian et al. 2004). The existence of this nitrogen “plateau” at low metallicities, implies that nitrogen cannot be treated as a pure “secondary” element. At extremely low metallicities Spite et al. (2005) have argued that there could be a second “plateau” at \([\text{N/Mg}] \sim -1.4\), reminiscent of what has been seen among Damped Lyman α galaxies (DLAs, Centurión et al. 2003), however the number of unmixed giants with measured nitrogen abundances, at extremely low metallicities is too small to draw any definitive conclusion.

5 Oxygen

In view of the current debate on the solar oxygen abundance, which ranges from the “oxygen starved” Sun of Asplund et al. (2004), with \(A(\text{O})=8.66\), to the “oxygen rich” Sun of Ayres et al. (2006), with \(A(\text{O})=8.84\), with the intermediate value of \(A(\text{O})=8.72\), derived from the latest 3D CO\(^5\)BOLD simulation of the solar atmosphere (Steffen 2006), I warn readers to always check what is the solar oxygen abundance adopted by any author before comparing values found in the literature.

For a long time it has been considered as firmly established that the \([\text{O/Fe}]\) ratio is constant among metal poor stars at a value \([\text{O/Fe}] \sim +0.4\), largely relying on the measurement of the \([\text{OI}]\) 630 nm line in metal-poor giants by Barbuy (1988). This view was first challenged by Abia & Rebolo (1989), who found a linear increase of \([\text{O/Fe}]\) with decreasing metallicities, based on the measurement of the OI permitted triplet at 777 nm. A similar increasing trend of \([\text{O/Fe}]\) was found by measurements based on the OH UV lines (Israelian et al. 1998; Boesgaard et al. 1999a; Israelian et al. 2001). On the other hand a “plateau” was found by Carretta et al. (2000), based on the measurement of both forbidden and permitted lines.

I think everybody now agrees that these discrepancies are rooted in the limitations of the analysis employed. In particular the combined effects of deviations from LTE and the effects of granulation (also referred to, as “3D effects”) on the different lines are difficult to assess.

In Fig. 1, I assembled the oxygen measurements in three recent papers but selecting only measurements based on the \([\text{OI}]\) forbidden line, which is the only line measured at the lowest metallicities, to avoid mismatches due to the use of different indicators. Taken at face value these results seem to support the existence of a linear increase in \([\text{O/Fe}]\), note however that the results of Cayrel et al. (2004) have not been corrected for the effects of granulation, because at present, no 3D model atmospheres suitable for this sample of metal-poor giants exist. The question remains therefore totally open and awaits a better understanding of the structures of the atmospheres of metal-poor stars.
6 Other $\alpha$–chain elements

All the even elements from oxygen to titanium can be formed by successive additions of $\alpha$-particles, the so-called $\alpha$–chain. The evolution of all the elements, Ne to Ti, should therefore resemble that of oxygen, although it need not to be necessarily identical, since the different elements are made in different layers, see Limongi & Chieffi (2003) for a review.

Mg, Si, Ca and Ti all show a plateau with constant $[X/Fe] \sim +0.4$, according to several recent investigations (Cayrel et al. 2004; Cohen et al. 2004; Barklem et al. 2005). For sulphur, instead, there is a situation similar to that of oxygen, with claims of a plateau-like behaviour (Chen et al. 2002; Nissen et al. 2004; Ryde & Lambert 2004), or of a linear rise with decreasing metallicities (Israelian & Rebolo 2001; Takada-Hidai et al. 2002). Korn & Ryde (2005) suggested that this was linked to the use of different S I lines by different investigators. However from the large sample of stars analysed by Caffau et al. (2005), who made use of lines of three different S I multiplets, it is obvious that at low metallicities some stars are found with $[S/Fe] \sim +0.4$, while others are found with considerably higher $[S/Fe]$ ratios, even when the same lines are used. Whether this discrepancy can be traced back to inadequacies of the model atmospheres or wrong atmospheric parameters, or whether it reflects a real scatter or bimodality in the Galactic $[S/Fe]$ distribution, is still an open question.

7 Iron peak elements

For iron peak elements the trends among extremely metal-poor stars already highlighted by McWilliam et al. (1995) and Ryan et al. (1996a) have been confirmed by the recent investigations (Cayrel et al. 2004; Cohen et al. 2004; Barklem et al. 2005). Namely Cr and Mn show an increasing deficiency over iron, with decreasing metallicity. Co, on the contrary, displays an increasing overabundance, while Ni tracks iron down to the lowest metallicities. The new important result of the recent investigations is the tiny star to star scatter in these abundance ratios at any given metallicity, showing that the scatter seen in the early investigations was entirely due to observational errors. Copper has been traced down to a metallicity of $[Fe/H] \sim -3$ using the Cu I 327 nm line (Bihain et al. 2004) and the $[Cu/Fe]$ ratio shows a marked decrease from the solar value, over the range $-2 \lesssim [Fe/H] \lesssim -1$. Below $[Fe/H] \sim -2$ it has a plateau-like behaviour with $[Cu/Fe] \sim -1$. Zinc tracks iron ($[Z/Fe]=0$) down to $[Fe/H]=2$ (Bihain et al. 2004) while at lower metallicities a linear increase is seen in $[Zn/Fe]$ up to $[Zn/Fe] \sim +0.7$ at metallicities $[Fe/H] \sim -4$ (Cayrel et al. 2004). It is remarkable that, in the metallicity range over which Zn tracks Fe, the ratio $[S/Zn]$ correlates very well $[\alpha/Fe]$ (Caffau et al. 2005), which justifies the use of $[S/Zn]$ as a “dust–free” proxy for $[\alpha/Fe]$ in DLAs (Centurión et al. 2000) and Blue Compact Galaxies.
8 Odd Z elements: Na, Al, K, Sc

The production of these elements is sensitive to the neutron excess (Arnett 1971) and may be influenced also by proton capture reactions occurring in the red-giant phase through the Ne-Na cycle (Langer et al. 1993), and the Mg-Al cycle (Denissenkov & Tout 2000). For Na the results of Cayrel et al. (2004) indicate a steady overdeficiency of Na over iron with decreasing metallicity. However these results are based on the Na i D lines, which are sensitive to departures from local thermodynamic equilibrium. Detailed NLTE computations by Andrievsky et al. (2007) show instead, that over the range $-4 \leq [\text{Fe}/\text{H}] \leq -2.5$ there is a constant overdeficiency of sodium over both iron and magnesium, with $[\text{Na}/\text{Fe}] \sim -0.21$ and $[\text{Na}/\text{Mg}] \sim -0.45$, for both “unmixed” giants and dwarfs. A few of the observed “mixed” giants display overabundances of sodium, which are likely the result of deep mixing and operation of the Ne-Na cycle. The combined effect of departures from LTE and granulation effects still needs to be determined. For Al the data indicate also a constant value with $[\text{Al}/\text{Fe}] \sim 0$, with a few Al enhanced stars among the “mixed” giants. Potassium has been observed for the first time in a large sample of stars by Cayrel et al. (2004), both K and Sc seem to show a very gentle decrease in their $[X/\text{Fe}]$ ratios with a moderate scatter of $\sim 0.12$ dex, always close to $[X/\text{Fe}] = 0$, although this slope is not very significant and a larger number of stars is needed to confirm its reality.

9 Neutron capture elements

The most obvious observational feature is the large scatter in the $[X/\text{Fe}]$ ratios, where X is any element with $Z > 30$, compared to the tiny scatter observed for the lighter elements. There is general consensus on the fact that this scatter is intrinsic and not driven by observational errors. In spite of the scatter one may notice trends of decreasing $[\text{Sr}/\text{Fe}]$, $[\text{Y}/\text{Fe}]$, $[\text{Ba}/\text{Fe}]$ and increasing $[\text{Eu}/\text{Fe}]$ with decreasing metallicity. Johnson & Bolte (2002) have been able to measure Pd and Ag in three very metal-poor stars, too few to be able to establish trends, however the $[\text{Pd}/\text{Ag}]$ ratios in these stars show a real difference from the corresponding solar system r-process ratio.

One exciting discovery has been the existence of the so-called r-enhanced stars, in which r-process products are enhanced, sometimes by a factor of ten or more, over iron. The first such star star discovered CS 22892-052 (Sneden et al. 1997) appeared to be unique, however, the discovery of CS 31082-001 (Cayrel et al. 2001) Hill et al. (2002) convinced people that there should be many stars of this class. In fact the dedicated survey HERES (Christlieb et al. 2004) Barklem et al. (2004) discovered 41 new ones and was furthermore able to demonstrate that they can be conveniently divided into two classes, r–II stars, for which $[\text{Eu}/\text{Fe}] > 1.0$ and r–I stars, for which $0.3 \leq [\text{Eu}/\text{Fe}] \leq 1.0$. Quite interestingly the r–II stars, are found in a narrow metallicity range centred at $[\text{Fe}/\text{H}] \sim -2.8$, with a tiny scatter (0.16 dex). The r–I stars, on the other hand, are found across
the entire metallicity range covered by the HERES survey and are much more common. Recently Frebel and collaborators (Frebel et al. 2007) have discovered another $r-$II star, HE 1523-0901 with $[\text{Fe}/\text{H}] = -3.1$ and $[\text{Eu}/\text{Fe}] = +1.8$.

A very intriguing result of the study of the $r-$enhanced stars is that there are probably multiple sites for the $r-$process, which would thus not be “universal” (Hill et al. 2002; Ishimaru et al. 2004; Wanajo & Ishimaru 2005; Honda et al. 2006). An example of our still poor understanding of the $r-$process is the measurement of lead in CS 31082-001 by Plez et al. (2004), the amount of lead measured is essentially all which is expected from the decay of Th and U, leaving none for the $r-$process production.

Lead can also be formed in the $s-$process and more efficiently in very metal-poor stars, due to the high neutron to iron seed ratio. The discovery of lead-rich extremely metal poor stars, like CS 29497-030 with $[\text{Pb}/\text{Fe}]=+3.5$ (Sivarani et al. 2004), demonstrates that the $s-$process is operating also at extremely low metallicities.

10 The hyper-metal-poor stars

This class of stars defined by Beers & Christlieb (2005) as stars with $-5 < [\text{Fe}/\text{H}] \leq -6$ currently contains only two stars: HE0107-5240 (Christlieb et al. 2002) and HE1327-2326 (Frebel et al. 2005). It should be however noted that these two stars have an extraordinary chemical composition with large enhancements of C,N and O so that their metallicity, meant as $Z$, is, in spite of the name of the class, comparable to that of metal-poor globular cluster stars. The recent downward revision of C,N,O abundances in these stars, based on 3D model atmospheres and LTE line formation, by Collet et al. (2006), places these stars at considerably lower $Z$.

11 CEMP stars

The Carbon Enhanced Metal Poor (CEMP) stars, are stars for which carbon is enhanced over iron. Beers & Christlieb (2005) suggest to define the class as stars with $[\text{C}/\text{Fe}] > +1$ although there is no general agreement on this. Among these some are true “carbon stars”, i.e. $\text{C}/\text{O} > 1$, spectroscopically recognisable by the presence of strong $\text{C}_2$ Swan bands. There is an ongoing debate on the frequency of CEMP stars, estimated to be $\sim 25\%$ by Marsteller et al. (2005) and only $14\%$ by Cohen et al. (2005). Many of these stars are binary and the C-enhancement is the result of mass-transfer from an AGB companion, currently in the white dwarf stage. Lucatello et al. (2005) found that the detected binary fraction among CEMP stars with enhancement of $s-$process elements is $68\%$, implying that the binary fraction among these stars is higher than among field stars. These authors also contend that in fact all these stars are in double or multiple systems.

It is quite likely that the CEMP class includes very diverse objects, Beers & Christlieb (2005) propose the following sub-classes: CEMP-r, which exhibit
$r-$process enhancement, the prototype star is CS 22892-052 (Sneden et al. [1994]);
CEMP-s, which exhibit $s-$process enhancement, prototype stars LP 625-44 and
LP 706-7 (Norris et al. [1997]), CEMP-r/s, which exhibit an enhancement pattern
that can be attributed to $s-$process and $r-$process, prototype star HE 2148-1247
(Cohen et al. [2003]); CEMP-no, stars which exhibit no enhancement of neutron
capture elements, prototype star CS 22957-027 (Norris et al. [1997], Bonifacio et al.
[1998]). Recently Sivarani et al. [2006] have discovered 2 CEMP dwarf stars CS
29528-041 and CS 31080-095 which show no enhancement in Sr, but a moderate
enhancement in Ba, for which they suggest a new class of CEMP-no/s which could
constitute a link between the CEMP-no and the CEMP-s stars.

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