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Exploring the early Universe with extremely metal-poor stars.

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Abstract. The earliest phases of Galactical chemical evolution and nucleosynthesis can be investigated by studying the old metal-poor stars. It has been recognized that a large fraction of metal-poor stars possess significant over-abundances of carbon relative to iron. Here we present the results of a 23-star homogeneously analyzed sample of metal-poor candidates from the Hamburg/ESO survey. We have derived abundances for a large number of elements ranging from Li to Pb. The sample includes four ultra metal-poor stars ([Fe/H] < -4.0), six CEMP-no stars, five CEMP-*s* stars, two CEMP-*r* stars and two CEMP-*r*/*s* stars. This broad variety of the sample stars gives us an unique opportunity to explore different abundance patterns at low metallicity.

Keywords. Galaxy: formation – Galaxy: halo – Stars: abundances – Stars: chemically peculiar Binaries: spectroscopic – ISM: structure

1. Introduction

The earliest stages of galaxy formation and chemical evolution can be explored by means of metal-poor stars. These very old stars are believed to hold the fossil record of the nucleosynthesis products of the first stars that formed shortly after the Big Bang. The vast majority of the metal-poor stars observed today are found in the Milky Way halo system.

Recent studies, such as Carollo *et al.*(2012), Lee *et al.*(2013), and Norris *et al.*(2013) confirm that carbon-enhanced metal-poor (CEMP) stars† constitute a large fraction of the most metal-poor stars known, and that the fraction of CEMP stars increases dramatically with decreasing metallicity, accounting for $\sim$40% of all stars with [Fe/H] $\leqslant -3.5$. The CEMP stars can be divided into four sub-classes defined by Beers & Christlieb (2005), the first being the CEMP-no stars which exhibit no over abundances of neutron-capture elements ([Ba/Fe] $\lesssim 0.0$). Several progenitors have been suggested for these stars such as fast rotating massive metal-free stars, the so-called "Spinstars" (Meynet *et al.* 2006, Hirschi 2007, Chiappini *et al.* 2008), supernovae with mixing and fallback (Umeda & Nomoto 2003,2005), and mass transfer from an asymptotic giant branch (AGB) binary companion (Masseron *et al.* 2010). The CEMP-no stars dominate at the lowest metallicity, hence these stars are most likely associated with elemental-abundance patterns that were produced by the very first generation of massive stars to form in the Galaxy.

† Originally defined by Beers & Christlieb (2005) as metal-poor ([Fe/H] $\leqslant -1.0$) stars with [C/Fe] $\geqslant +1.0$; a level of carbon enrichment [C/Fe] $\geqslant +0.7$ is used in most contemporary work.

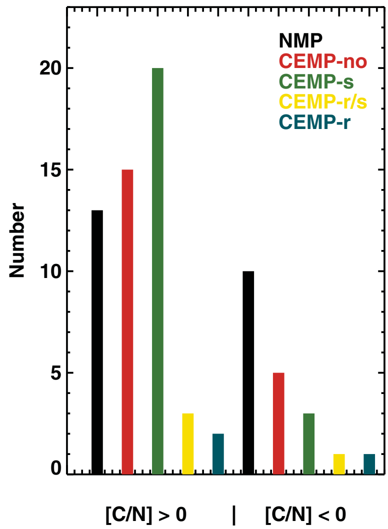

Figure 1. Number of stars with either [C/N] $>$ 0 or [C/N] $<$ 0 for the different types of metal-poor stars. Black: NMP stars, red: CEMP-*no* stars, green: CEMP-*s* stars, blue: CEMP-*r* stars, yellow: CEMP-*r*/*s* stars (from left to right for each group).

The second sub-class are the CEMP-*s* stars, which show over abundances of neutron-capture elements produced in the slow neutron-capture process ([Ba/Fe] $>$ 1.0). These are widely believed to be the result of mass transfer from an AGB binary companion, a scenario also supported by radial-velocity monitoring of these stars (Lucatello *et al.* 2003 and Hansen *et al.* 2015b submitted). The two last sub-classes of CEMP stars are the CEMP-*r* and CEMP-*r*/*s*. The first show over abundances of element produced in the rapid neutron-capture process ([Eu/Fe] $>$ 1.0), and the latter exhibit over abundances of neutron-capture elements suggesting contributions from both the *s*- and *r*-process (0.0 $<$ [Ba/Eu] $<$ 0.5). Only few stars belonging to these two sub-classes have been detected and analysed. Each of these sub-classes appear to be associated with different element-production histories, thus their study provides insight into the variety of astrophysical sites in the early Galaxy that were primarily responsible for their origin.

2. Mixing in the early Universe

All of the proposed progenitors of CEMP stars have experienced some degree of internal mixing, whether that mixing is due to convection driven by rapid rotation in the spinstars, or convection in AGB stars during their evolution (Herwig 2005). When this mixing occurs the carbon is transported from the core (spinstars) or from the surface (AGB stars) to the H-burning shell where the CNO cycle is active, where it is transformed into ^{13}C and ^{14}N. Thus the mixing creates a signature we can detect in the C and N abundances and in the ^{12}C/^{13}C isotopic ratio of the un-evolved CEMP star. High ^{12}C/^{13}C and [C/N] ratios indicate only partial hydrogen burning by the CNO cycle, while low ^{12}C/^{13}C and [C/N] ratios are a signature of more complete burning by the CNO cycle (Maeder *et al.* 2015).

We have therefore divided the stars into two groups; one with [C/N] $>$ 0 ([C/Fe] $>$ [N/Fe]) and one with [C/N] $<$ 0 ([C/Fe] $<$ [N/Fe]). Figure 1 shows the number of each type of metal-poor star with either [C/N] $>$ 0 or [C/N] $<$ 0. There are clearly more stars with [C/N] $>$ 0 than with [C/N] $<$ 0. For the "normal" metal-poor (NMP) stars the numbers are roughly equal, while the CEMP-no and especially the CEMP-*s* stars are of the [C/N] $>$ 0 variety.

Figure 2 shows the C and N abundances and the [C/N] ratios, of the sample of stars along with those from Yong *et al.*(2013), as a function of metallicity. Circles represent stars with [C/N] $>$ 0 and triangles stars with [C/N] $<$ 0. From inspection of the bottom panel of Figure 2, none of the CEMP-no stars with [C/N] $<$ 0 are found with metallicities above [Fe/H] > -3.4; all CEMP-no

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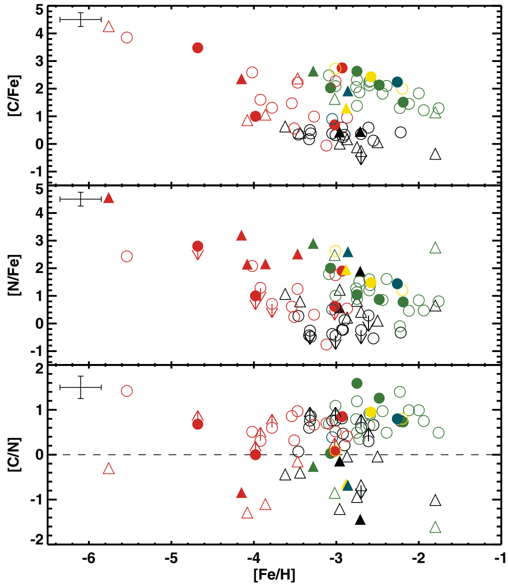

Figure 2. C and N abundances and [C/N] ratios, filled symbols – Hansen *et al.*(2015a), unfilled symbols – Yong *et al.*(2013). Circles represent stars with [C/N] > 0; triangles are stars with [C/N] < 0. Symbols are color-coded (black: NMP stars, red: CEMP-*no* stars, green: CEMP-*s* stars, blue: CEMP-*r* stars, yellow: CEMP-*r*/*s* stars). An approximate error bar for the sample stars is shown in the upper left of each panel.

stars with [C/N] < 0 are at the extremely low-metallicity end. Some CEMP-no stars are found to have large enhancements in Na and Mg. In our sample these stars are only found below this extremely low metallicity, as can be seen in Figure 3, where Na, Mg and Al abundances for the stars are plotted against metallicity. This indicates that the large degrees of internal mixing and processing required to produce the abundance pattern seen in such CEMP-no stars was only operating at the very earliest times.

As mentioned above the mixing also alters the $^{12}C/^{13}C$ isotopic ratio. We find low (~ 5) $^{12}C/^{13}C$ isotopic ratios for all of our CEMP-no stars, consistent with the equilibrium value for CNO-cycle processed material ($^{12}C/^{13}C \sim 4$). This shows that the material from which these stars formed has undergone mixing, whether in spinstars or in some pre-supernova evolution. The $^{12}C/^{13}C$ isotopic ratios found in the CEMP-*s* stars of our sample are generally higher (~ 13). This value is low enough to be a signature of H-burning via the CNO cycle, which is also expected if the carbon excess found in CEMP-*s* stars is due to mass transfer from an AGB companion, where multiple dredge up events mix the material in the star. However, according to Bisterzo *et al.* (2012), current AGB models do not include sufficient mixing to replicate the low $^{12}C/^{13}C$ isotopic ratios found in CEMP-*s* stars.

3. Carbon bands and Ba floor

It has been suggested by Spite *et al.* (2013) that the absolute C abundances of CEMP stars fall into two bands. The C abundances for stars with metallicities [Fe/H] > -3 appeared to cluster around the solar carbon abundance (A(C) ~ 8.5), while those with [Fe/H] < -3 cluster around a lower C abundance, A(C) ~ 6.5. The higher band is mainly populated by CEMP-*s* stars that are thought to have gained their carbon from an extrinsic source (i.e., mass transfer from an AGB binary companion), whereas the lower band is mainly populated by CEMP-no stars that are believed to be born with their carbon excess. The recent paper by Bonifacio *et al.*(2015) confirms the existence of the two carbon bands for a larger sample, including the stars from Yong *et al.*(2013).

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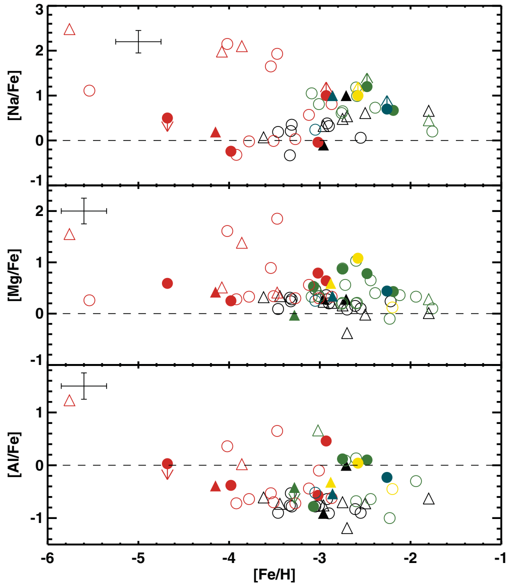

Figure 3. [Na/Fe], [Mg/Fe], and [Al/Fe] for the stars from Hansen *et al.*(2015a) (filled symbols) and Yong *et al.*(2013) (unfilled symbols). Color-coding of the stellar classes is as in Figure 2. An approximate error bar for the sample stars is shown in the upper left of each panel.

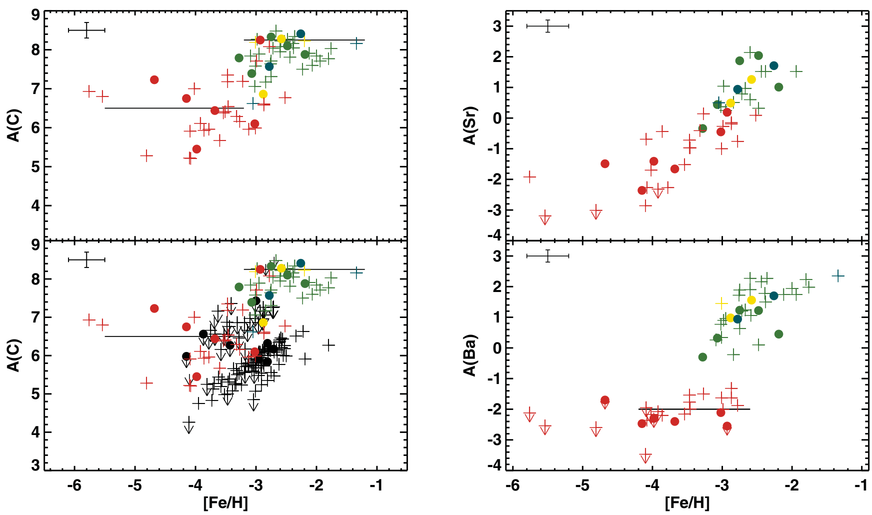

Figure 4. Absolute C, Sr, and Ba abundances for the sample stars (dots: Hansen *et al.*(2015a); plusses: Yong *et al.*(2013)), colour coding as in Figure 2. C-bands and Ba floor are indicated by solid lines.

The left panels of Figure 4 show the distribution of absolute C abundances for our stars (Hansen *et al.* 2015a) and those of Yong *et al.* (2013). Our data also support the presence of two carbon "bands" that comprise the distribution of the absolute carbon abundances for CEMP stars, although with a smoother transition between the bands than was found by Spite *et al.*(2013). However a few of the CEMP-no stars with metallicities above $[Fe/H] > -3.0$ have carbon abundances on the higher band, indicating a different origin for the carbon found in these stars as opposed to those with carbon abundances on the lower band.

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It can also bee seen from Figure 4 that the CEMP-*r* and CEMP-*r*/*s* stars are found at both the high and the low levels of C enhancement. There is as such no indication of a possible dominance of either high or low carbon-abundance stars for either of these CEMP sub-classes.

The right panels of Figure 4 show the absolute Sr and Ba abundances for the CEMP stars in our sample (Hansen *et al.* 2015a) and those of Yong *et al.* (2013). There is clear grouping of the different classes of stars considered in our study. Recall that [Ba/Fe] is used to differentiate the CEMP-no stars from the CEMP-*s* and CEMP-*r*/*s* stars. For the Sr abundances we see that the individual classes of the stars in our sample are mixed together in a band showing decreasing A(Sr) with decreasing [Fe/H], but with a possible change in the trend at the lowest metallicity (around [Fe/H] ~ -4.2). In contrast, the behaviour of Ba for the CEMP-no stars in our sample is substantially different, the stars for which we have Ba detections exhibit Ba abundances of A(Ba) ~ -2.0, independent of metallicity. It should be emphasized though, that the area below [Fe/H] $= -4$ is only sparsely populated, with most stars only having an upper limit on Sr and Ba. Never the less the current data suggest the presence of a floor in Ba at extremely low metallicity.

4. Summary

We have here presented some of the key results of an homogeneous abundance analysis of 23 extremely metal-poor stars found in the Milky Way halo. A large fraction of these are carbon enhanced, and from inspection of their C and N abundances along with ^{12}C/^{13}C ratios, we see signs of mixing having occurred in the progenitors of these stars. For the CEMP-no stars the results indicate that this mixing was most efficient at the lowest metallicities. Our sample confirms the presence of two bands in the absolute C abundances of CEMP stars, as suggested by Spite *et al.*(2013). However, the presence of CEMP-no stars on both bands challenges the interpretation as purely intrinsic/extrinsic C origin. Finally we detect different behavior for the absolute abundances for the two neutron-capture elements Sr and Ba, where an indication of a floor is seen in the Ba abundances of CEMP-no stars.

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