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Very Metal-Poor Stars and the Early Universe

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Abstract. Very metal-poor stars ([Fe/H] < –2.0) inform our understanding of the formation and evolution of the Galaxy, and the physical conditions in the earliest star-forming environments of the Universe. They play an integral part in the paradigms of stellar populations, stellar archaeology, and near-field cosmology. We review the carbon-rich and carbon-normal sub-populations of the most iron-poor stars, providing insight into chemical enrichment at the earliest times in the Universe. We also discuss the role of very metal-poor stars in providing insight into the Galaxy's halo, thick disk, and bulge, and the promise they hold for the future. A comparison between the abundances obtained for the nine most Fe-poor stars ([Fe/H] < –4.5) (all but one of which is C-rich) with abundances obtained from far-field cosmology suggests that the former are the most chemically primitive objects yet observed and probably older than the DLA- and sub-DLA systems for which data are currently available from far-field studies.

Keywords. Early Universe, Galaxy: abundances, Galaxy: bulge, Galaxy: halo

1. Paradigms and assumptions

The Big Bang paradigm tells us that after the first few minutes the Universe consisted only of hydrogen, helium, and lithium with relative mass densities of 0.75, 0.25, and 2.3×10^{-9}, respectively, and that after a further few 100 Myr the first galaxies and stars formed. Since then, essentially all of the heavy elements have been synthesized in stars, and a basic assumption is that the most metal-poor stars are the best available candidates to take us to the earliest stellar generations and to the Big Bang. This is the working hypothesis that drives stellar archaeology and near-field cosmology. Insofar as the Galaxy's halo globular clusters have a mean abundance [Fe/H] $\sim$ –1.6, and ages of order 10 Gyr, which are not too dissimilar to the age of the Universe (13.8 Gyr), it is reasonable to assume that the very metal-poor ([Fe/H] < –2.0†) stars of the Milky Way are very likely the best probes of the chemical enrichment of the Universe at the earliest times.

Where in the Galaxy are these objects to be found? We shall consider three cases. The first is the Galactic bulge, where the first stars formed in the Galaxy; the second is the Milky Way dwarf galaxy satellites; and the third is the Galaxy's stellar halo population. In order of accessibility, we note that the bulge is very crowded; the dwarf galaxies are very far away; while the nearby halo stars are just right.

2. The rationale for studying very metal-poor stars

- *An essential tool for the stellar populations paradigm, for stellar archaeology, and for near-field cosmology*

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† Following the terminology of Beers & Christlieb (2005)

- *The stars closest to the Big Bang*
- *Formed at redshifts > 4 – 5 (some 13 billion years ago) – probe conditions when the first heavy element producing objects formed*
- Lithium constrains Big Bang nucleosynthesis
- Insight into the Initial Mass Function at the earliest times
- *Constrain explosions of the first SNe and how the first elements were formed*
- Information on the manner in which SN ejecta were incorporated into later generations
- *Constrain the manner in which the Galaxy and its stellar populations formed*
- Determine ages of the first stars with the Th and U chronometers

In what follows we shall consider only the items above which are italicized.

3. Discovery

In the solar neighborhood, very metal-poor stars, of which the large majority known today are members of the halo, are rare. Accordingly, several different techniques have been used to increase the likelihood of discovering them. Here is a list of most of the probes/techniques, with examples. For more details see Beers & Christlieb (2005) and Frebel & Norris (2013, 2015).

- Informed serendipity: some very metal-poor stars have been included in catalogs unrelated to their metallicity. An example is CD−38° 245 (in an A-star catalog; [Fe/H] = –4.0, Bessell & Norris 1984).
- High-proper-motion stars: Ryan & Norris (1991), Carney *et al.* (1996).
- Objective prism surveys: Bidelman & MacConnell (1973), Beers *et al.* (1992) (HK survey), Christlieb *et al.* (2008) (HES Survey).
- Spectroscopic surveys: Sloan Digital Sky Survey (SDSS) & its extension SEGUE, RAVE, LAMOST, and GALAH.
- Photometric surveys: SkyMapper (uvgriz) (Keller *et al.* 2007, Howes 2016); Pristine (Starkenburg *et al.* 2017) (Ca H & K filter+(existing)ugriz); and Gaia.

In the early 1950s it was universally believed that all stars had the same chemical abundance as the Sun. The paradigm shift from this position was made by Chamberlain & Aller (1951) who first demonstrated the existence of stars having [Fe/H] < –2.0. Over the ∼70 years since then, stars with lower and lower abundances have been discovered, until today the star with the lowest abundance has [Fe/H] < –7.3, with [Ca/H] = –7.2 (Keller *et al.* 2014). Figure 1 shows a plot of the [Ca/H] value of the star with the lowest abundance as a function of the date of its discovery. Also shown are predictions of the lowest abundance that one might expect in the Milky Way.

4. The most Fe-poor stars

The first star with [Fe/H] ∼ –4.0 was discovered in 1984. Such stars are extremely rare: in the solar neighbourhood we expect ∼1 star in a million to have an abundance this low. The search for objects with abundances smaller than this began in 1980, and it was not until 2002 that such an object was found. Table 1 contains data for the nine stars currently known to have [Fe/H] < –4.5.

Figure 2 presents spectra for stars with abundances in the [Fe/H] range <–7.3 to –0.9. For the top three stars the metal lines become weaker going from top towards bottom, consistent with the abundances shown in the figure. In the bottom two spectra, however, there are large numbers of lines that are stronger than one might have expected. Most of these are CH lines, resulting from very large relative carbon abundances. This is of

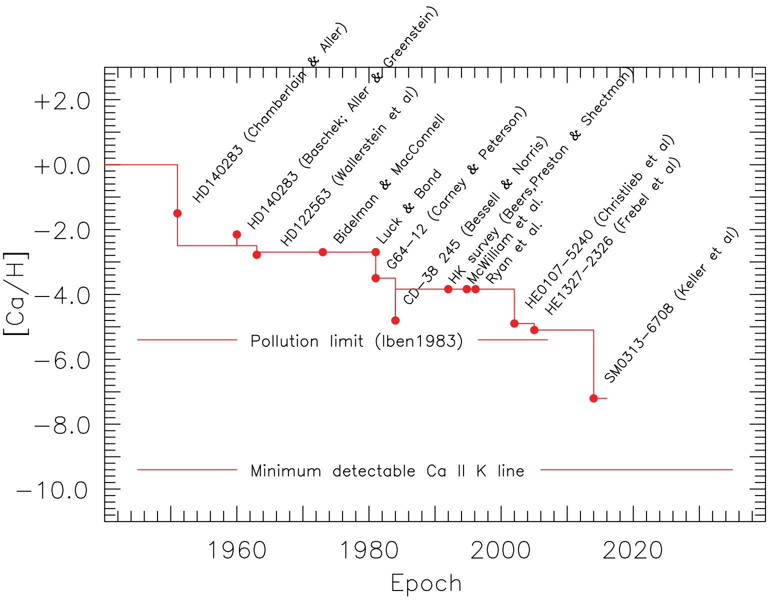

Figure 1. Calcium abundance, [Ca/H], of the most Fe-poor star then known, as a function of epoch of discovery. See Frebel & Norris (2013, 2015) for more details.

Table 1. The nine most Fe-poor stars

Object (1)	RA (2000) Dec (2)	T_{eff} (3)	log g (4)	[Fe/H] (5)	[C/Fe] (6)	Sources (7)
SM 0313−6708	03 13 00.4 −67 08 39.3	5125	2.30	<−7.30	>+4.9	[1]
HE 1327−2326	13 30 06.0 −23 41 49.7	6180	3.70	−5.66	+4.3	[2]
HE 0107−5240	01 09 29.2 −52 24 34.2	5100	2.20	−5.39	+3.7	[3]
SD 1035+0641	10 35 56.1 +06 41 44.0	6262	4.00	<−5.07	>+3.5	[4]
SD 1313−0019	13 13 26.9 −01 19 41.4	5200	2.60	−5.00	∼+3.0	[5]
SD 1742+2531	17 42 59.7 +25 31 35.9	6345	4.00	−4.80	+3.6	[4]
HE 0557−4840	05 58 39.3 −48 39 56.8	4900	2.20	−4.75	+1.6	[6]
SD 1029+1729	10 29 15.2 +17 29 28.0	5811	4.00	−4.73	<+0.9	[7]
HE 0233−0343	02 36 29.7 −03 30 06.0	6100	3.40	−4.68	+3.5	[8]

Sources – [1] Keller *et al.* (2014); [2] Frebel *et al.* (2005), Aoki *et al.* (2006); [3] Christlieb *et al.* (2004); [4] Bonifacio *et al.* (2015); [5] Frebel *et al.* (2015); [6] Norris *et al.* (2007); [7] Caffau *et al.* (2012); [8] Hansen *et al.* (2014)

fundamental significance. Indeed, for [Fe/H] < –4.5, eight of the nine stars currently known are carbon rich, and inspection of the sixth column of Table 1 shows that seven of them have [C/Fe] > 3.0, a relative overabundance of 1000! Said differently, 80% of stars with [Fe/H] < –4.5 are extremely carbon rich.

In Figure 3, the left panel presents [C/Fe] vs [Fe/H] for very metal-poor stars, with normal stars as full symbols, and C-rich objects as circled dots for CEMP-s, r/s and r stars (enhanced heavy neutron-capture-element abundances) and circled crosses for CEMP-no stars (no heavy neutron-capture-element enhancement). The horizontal line at [Ca/Fe] = 0.7 separates the C-rich and C-normal stars.† In the right panel the generalized histograms are shown for the CEMP-no stars on the left (thick line) and the other classes on the right (thin line). A second fundamental characteristic of the CEMP-no stars is

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† For definitions of CEMP stars see Beers & Christlieb (2005) and Aoki *et al.* (2007).

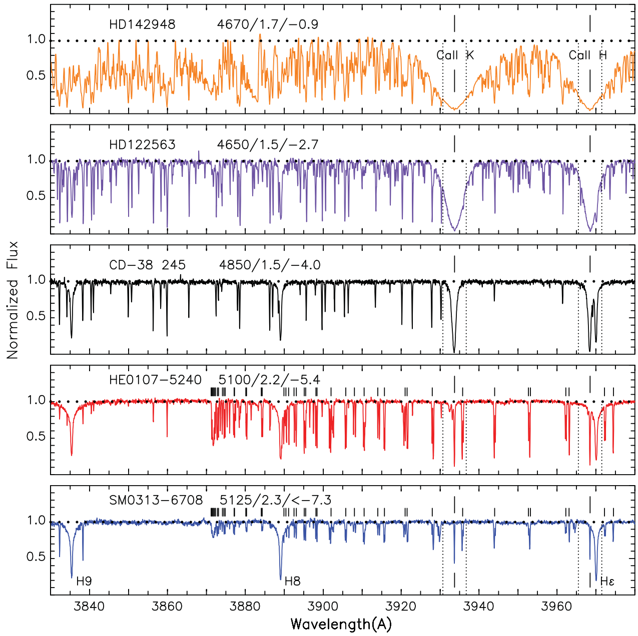

Figure 2. Spectra of stars with similar $T_{\rm eff}$ and $\log g$ in the [Fe/H] range < -7.3 to -0.9. The upper legends contain $T_{\rm eff}$ /$\log g$/[Fe/H]. Figure reproduced from Frebel & Norris 2015.

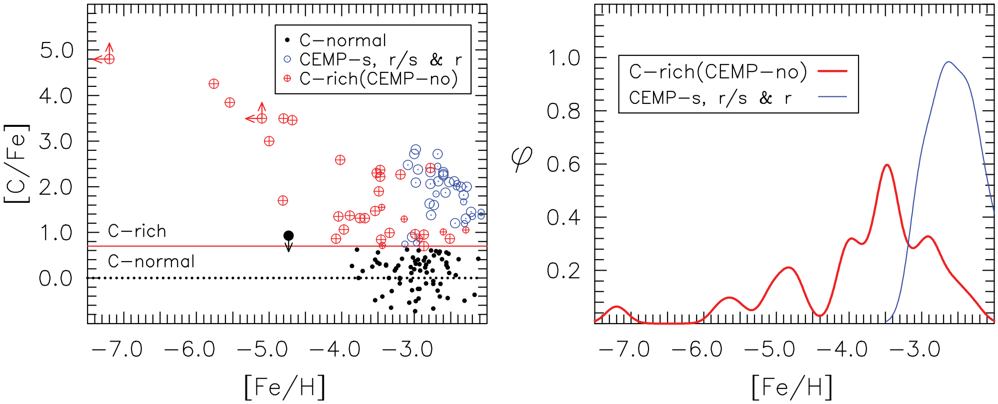

Figure 3. [C/Fe] vs. [Fe/H] for C-normal and C-rich stars (left), and generalized [C/Fe] histograms for C-rich stars (right).

that most of them also show large overabundances of some or all of the light elements N, O, Na, Mg, Al, and Si, but not for Ca and elements heavier that this (e.g., Norris *et al.* 2013).‡ This behavior is strongly suggestive of an origin of the CEMP-no star overabundances in nuclear processes occurring in the outer regions, rather than in the deep interiors, of the progenitors of these stars.

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‡ We also refer the reader to the recent work of Yoon *et al.* (2016), who report "evidence for multiple progenitors of the CEMP-no stars", based on consideration of a number of CEMP components in the (A(C), [Fe/H]) – plane (where $A(C) = \log(N_C/N_H) + 12$).

5. Some potential ingredients for an explanation of the most Fe-poor ([Fe/H] < –4.5), C-rich (CEMP-no) stars

What is the origin of this C-rich first population of stars in the Universe? Here is a list the author considers to contain the most likely ingredients for a solution.

- Fine-structure line transitions of CI and OII as a major cooling agent in the early Universe (Bromm & Loeb 2003, Frebel *et al.* 2007)
- Supermassive ($M > 100\ M_\odot$), rotating stars (Fryer *et al.* 2001)
- Multiple generations of Type II supernovae involving “fallback”($M \sim 10 - 40\ M_\odot$ stars) (Limongi *et al.* 2003, Heger & Woosley 2010)
- Zero-metallicity, “mixing and fallback” Type II SNe ($M \sim 10 - 40\ M_\odot$ stars) (Umeda & Nomoto 2003)
- Zero-metallicity, rotating, massive ($\sim 60\ M_\odot$) and intermediate mass ($\sim 7\ M_\odot$) “spin-stars” (Meynet *et al.* 2006, 2010)
- Different efficiency of expulsion from “mini dark halos” of the ejecta on SNe having high energy (C-normal) and low energy (C-rich) ejecta (Cooke & Madau 2014)

For a more exhaustive description see Frebel & Norris (2015). One possibility not included here is the suggestion of Suda *et al.* (2004) that the most Fe-poor, C-rich stars are binaries. While binarity provides an explanation for the CEMP-s stars, the currently available data support the view that the CEMP-no stars have a binary fraction similar to that of C-normal Population II stars (see Starkenburg *et al.* 2014, and references therein).

6. A scenario for the earliest times

- The first stars form in “mini dark halos” from material comprising H and He; the cooling is provided by molecular hydrogen; and the mass function of these objects is top-heavy ($M > 20 - 300\ M_\odot$). None of these objects survives until the present time.
- Some fraction of the first population synthesizes large amounts of carbon and oxygen, as described by some exotic stellar evolutionary models (the rotating $60 - 300\ M_\odot$ stars of Meynet *et al.* (2006) and Fryer *et al.* (2001) and the “mixing-and-fallback” models of Umeda & Nomoto (2003)).

During subsequent star formation, material with large enhancements of carbon and oxygen cools via the fine structure lines of CII and OI, and fragments to form low-mass, long-lived stars still observed today.

This is the C-rich population.

- The remainder of the first generation stars does not produce large amounts of carbon, but rather more solar-like abundance patterns.
- This material has more difficulty in cooling and fragmenting, but several possibilities exist (e.g. dust-induced star formation, Schneider *et al.* 2006). A second channel forms carbon-normal, low-mass, long-lived stars, on a longer timescale.

This is the C-normal population.

7. Other components of the Galaxy

7.1. *Galactic satellites*

The discovery and analysis of the Galaxy’s ultra-faint dwarf galaxy satellites have led to a significant sample of very metal-poor stars, and interesting comparisons with those of the Galaxy’s stellar halo. An important characteristic of these systems is that those having smaller baryonic mass have lower metallicity. In the present context, the Segue 1 ultra-faint dwarf system, which has a baryonic mass of only $\sim 1000\ M_\odot$, is of great interest. Frebel *et al.* (2014) have presented chemical abundances for seven of its red giant branch

(RGB) members, which cover the range $-1.4 < [\mathrm{Fe/H}] < -3.8$. Of these objects, three have $[\mathrm{Fe/H}] < -3.5$, all of which are CEMP-no stars, while a fourth is a CEMP-s star. Space does not permit further discussion here; but, that said, there is a clear connection between the increase of the C-rich fraction with decreasing [Fe/H], which we have seen above for the very metal-poor stars of the Galactic halo.

7.2. *The Galaxy's inner and outer halos*

One of the important results to emerge from the data explosion described in Section 2 (in this case SDSS) is the result of Carollo *et al.* (2007) that the Galaxy's halo can be well described in terms of a system having inner and outer components.† The inner and outer components dominate inside and outside 15 – 20 kpc, respectively. Two essential physical differences between them is that they have different mean abundances, $[\mathrm{Fe/H}]_{\mathrm{inner}} = -1.6$ and $[\mathrm{Fe/H}]_{\mathrm{outer}} = -2.2$, and systemic rotational velocities $\langle V_{\phi} \rangle_{\mathrm{inner}} = 7 \pm 4$ and $\langle V_{\phi} \rangle_{\mathrm{outer}} = -80 \pm 13$ kms^{-1}. While we must await definitive confirmation of a dual halo from Gaia, two recent works support the claim. First, Fernández-Alvar *et al.* (2017), confirm the duality with APOGEE data, and demonstrate that $[\alpha/\mathrm{Fe}]$ is smaller by 0.1 dex in the outer halo (for stars with $[\mathrm{M/H}] > -1.1$). Second, Helmi *et al.* (2017), using Gaia and RAVE data, report a retrograde halo component consistent with that of the Carollo *et al.* model.

7.3. *The "metal-weak" tail of the thick disk*

The "metal-weak" tail of the thick disk was first defined by Morrison *et al.* (1990), based at least in part on analysis of the Bidelman & MacConnell (1973) sample by Norris *et al.* (1985), which was questioned by Ryan & Lambert (1995). With a more comprehensive data set of the Bidelman-MacConnell stars and another sample, the bright HES stars, Beers *et al.* (2014, 2017) have now clearly confirmed the existence of this component, with abundances down to $[\mathrm{Fe/H}] \sim -2.5$.

What still remains unclear, however, is the relationship of the "metal-weak" tail to the canonical thick disk component. An investigation which has the methodology to potentially address this question is the work of Ruchti *et al.* (2010) which uses the RAVE results to kinematically define the components of the Galaxy (in terms of halo, halo/intermediate thick disk, thick disk, thick disk/intermediate thin disk, and thin disk components). In plots of Ruchti *et al.* data in the $[\alpha/\mathrm{Fe}]$ versus [Fe/H] plane, one clearly sees stars of Ruchti's halo, halo/intermediate thick disk, and thick disk components that stretch down to $[\mathrm{Fe/H}] \sim -2.5$. While the available sample is insufficient to settle this issue, as more data become available the MDF of such samples may be able to do so.

We also note the important conclusion of Ruchti *et al.* (2010), based on the similarity of the halo and thick disk distributions in the $[\alpha/\mathrm{Fe}]$ versus [Fe/H] plane "that the α-enhancement of the metal-poor thick disk implies that direct accretion of stars from dwarf galaxies similar to surviving dwarf galaxies today did not play a major role in the formation of the thick disk".

7.4. *The bulge*

The search for very metal-poor stars in the Galactic bulge is extremely difficult given the crowded nature of the field. Recently, this has become more feasible with the SkyMapper project and the work of Howes (2016, and references therein)‡. For the first time, stars have been identified in the bulge with [Fe/H] values as low at -4.0, and high-resolution relative abundances [X/Fe] obtained for 37 of these RGB stars. Of particular interest

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† See Schönrich *et al.* (2011) for an alternative view; and Beers *et al.* (2012) for counterpoint.

‡ https://openresearch-repository.anu.edu.au/handle/1885/104573

is the report: “Two notable differences are the absence of carbon-enhanced metal-poor bulge stars, and the α-element abundances exhibit a large intrinsic scatter and include stars which are underabundant in these typically enhanced elements.” Concerning the α-elements, one sees some 15% of objects lying below the bulk of the stars in the range $-4.0 < \mathrm{[Fe/H]} < -2.0$. It will be interesting to see if further work confirms this result, which is reminiscent of low values of $[\alpha/\mathrm{Fe}]$ in the dwarf spheroidal galaxies (albeit at higher values of [Fe/H]). On the other hand, the absence of CEMP stars may not be of astrophysical significance, but rather the result of the SkyMapper abundance sensitive “v” filter including carbon sensitive features in its bandpass. See Jacobson *et al.* (2015) for a similar effect in a large metal-poor sample based on SkyMapper data.

8. Near-field cosmology meets far-field cosmology

We conclude by comparing the near-field cosmology results discussed here for the abundances of the most Fe-poor stars – in particular the fact that of the nine stars with $\mathrm{[Fe/H]} < -4.5$, seven have extremely large relative carbon abundances, $\mathrm{[C/Fe]} > +3.0$ – with those obtained from far-field cosmology investigations of Lyman-α clouds. From the high spectral resolution abundance determinations of Cooke *et al.* (2011, 2012), Becker *et al.* (2012), and references therein, of damped Ly-α (DLA) and sub-DLA systems, one finds that at most only one of $\sim$10 – 15 objects has $\mathrm{[C/Fe]} > +1.0$. Concerning the comparison of this result with the abundances of carbon in the most Fe-poor stars in the Milky Way, Becker *et al.* suggest: “If carbon-enhanced stars fairly reflect their native ISM abundances, then these abundances are no longer common by redshift of $z \sim 6$. This raises the intriguing possibility that most carbon-enhanced stars were formed at even earlier times”. The data are consistent with the view that the near-field Fe-poor stars with $\mathrm{[Fe/H]} < -4.5$ are the most chemically primitive objects yet observed. (See Frebel & Norris 2015 for further details.)

9. Take-home messages

- Very metal-poor stars play a pivotal role in the stellar populations paradigm, stellar archaeology, and near-field Cosmology.
- At the earliest times (within a few 100,000 Myr of the Big Bang) there were two distinct populations of stars – one of them C-rich (CEMP-no), the other C-normal.
- Below $\mathrm{[Fe/H]} = -4.5$, eight of the nine stars currently known are C-rich.
- CEMP-no stars also exist in the Galaxy’s dSph and ultra-faint dwarf galaxy satellites. In Segue 1, three of seven RGB stars analyzed to date are CEMP-no.
- The two carbon populations may be understood in terms of very early chemical enrichment by SNe that experienced “fallback” or “mixing and fallback” during their explosion and/or by rotating, massive ”spinstars”. The available data do not support an explanation involving binarity.
- As the result of large surveys, very metal-poor stars are becoming more evident in the thick disk, leading (potentially) to further insight into its nature. A similar statement applies to the Galaxy’s “inner-halo, outer-halo” dichotomy, as well as to its bulge populations.
- Comparison of near-field and far-field cosmological results suggests that the C-rich stars with $\mathrm{[Fe/H]} < -4.5$ are the most chemically primitive objects yet observed and probably older than objects for which data are currently available in the far-field.

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