

Metal-poor Stars

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Abstract. The abundance patterns of metal-poor stars provide us a wealth of chemical information about various stages of the chemical evolution of the Galaxy. In particular, these stars allow us to study the formation and evolution of the elements and the involved nucleosynthesis processes. This knowledge is invaluable for our understanding of the cosmic chemical evolution and the onset of star- and galaxy formation. Metal-poor stars are the local equivalent of the high-redshift Universe, and offer crucial observational constraints on the nature of the first stars. This review presents the history of the first discoveries of metal-poor stars that laid the foundation to this field. Observed abundance trends at the lowest metallicities are described, as well as particular classes of metal-poor stars such as r-process and C-rich stars. Scenarios on the origins of the abundances of metal-poor stars and the application of large samples of metal-poor stars to cosmological questions are discussed.

1. Introduction

The first stars that formed from the pristine gas left after the Big Bang were very massive (Bromm et al. 2002). After a very short life time these co-called Population III stars exploded as supernovae, which then provided the first metals to the interstellar medium. All subsequent generations of stars formed from chemically enriched material. Metal-poor stars that are observable today are Population II objects and belong to the stellar generations that formed from non-zero metallicity gas. In their atmospheres these objects preserve information about the chemical composition of their birth cloud. They thus provide archaeological evidence of the earliest times of the Universe. In particular, the chemical abundance patterns provide detailed information about the formation and evolution of the elements and the involved nucleosynthesis processes. This knowledge is invaluable for our understanding of the cosmic chemical evolution and the onset of star- and galaxy formation. Metal-poor stars are the local equivalent of the high-redshift Universe. Hence, they also provide us with observational constraints on the nature of the first stars and supernovae. Such knowledge is invaluable for various theoretical works on the early Universe.

Focusing on long-lived low-mass ($\sim 0.8 M_{\odot}$) main-sequence and giant metal-poor stars, we are observing stellar chemical abundances that reflect the composition of the interstellar medium during their star formation processes. Main-sequence stars only have a shallow convection zone that preserves the stars' birth composition over billions of years. Stars on the red giant branch have deeper convection zones that lead to a successive mixing of the surface with nuclear burning products from the stellar interior. In the lesser evolved giants the

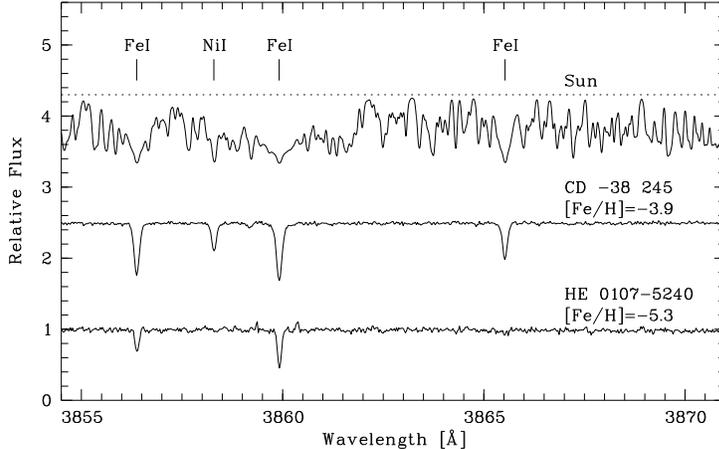


Figure 1. Spectral comparison of the Sun with the metal-poor stars CD -38° 245 and HE 0107–5240. Figure taken from Christlieb et al. (2004).

surface composition has not yet been significantly altered by any such mixing processes. The main indicator used to determine stellar metallicity is the iron abundance, $[\text{Fe}/\text{H}]$, which is defined as $[A/B] = \log_{10}(N_A/N_B)_* - \log_{10}(N_A/N_B)_{\odot}$ for the number N of atoms of elements A and B , and \odot refers to the Sun. With few exceptions, $[\text{Fe}/\text{H}]$ traces the overall metallicity of the objects fairly well.

To illustrate the difference between younger metal-rich and older metal-poor stars, Figure 1 shows spectra of the Sun and two of the most metal-poor stars, CD -38° 245 (Bessell & Norris 1984) and HE 0107–5240 (Christlieb et al. 2002). The number of the atomic absorption lines detectable in the spectra decreases with increasing metal-deficiency. In HE 0107–5240, only the intrinsically strongest metal lines are left to observe. Compared with the metal-poor stars presented in the figure, in a spectrum of a similarly unevolved Population III object, no metal features would be detectable since it contains no elements other than H, He and Li at its surface.

Large numbers of metal-poor Galactic stars found in objective-prism surveys in both hemispheres have provided enormous insight into the formation and evolution of our Galaxy (e.g., Beers & Christlieb 2005). However, there is only a very small number of stars known with metallicities below $[\text{Fe}/\text{H}] < -3.5$. The number of known metal-poor stars decreases significantly with decreasing metallicity as illustrated in Figure 2. Objects at the lowest metallicities are extremely rare but of utmost importance for a full understanding of the early Universe. Abundance trends are poorly defined in this metallicity range, and the details of the metallicity distribution function (MDF) at the lowest metallicity tail remains unclear. A major recent achievement in the field was the push down to a new, significantly lower limit of metallicity $[\text{Fe}/\text{H}]$ measured in a stellar object: From a longstanding $[\text{Fe}/\text{H}] = -4.0$ (CD -38° 245; Bessell & Norris 1984) down to $[\text{Fe}/\text{H}] = -5.3$ (HE 0107–5240; Christlieb et al. 2002), and very recently, down to $[\text{Fe}/\text{H}] = -5.4$ (HE 1327–2326; Frebel et al. 2005). Overall, only three stars are known with iron abundances of $[\text{Fe}/\text{H}] < -4.0$. The recently discovered star

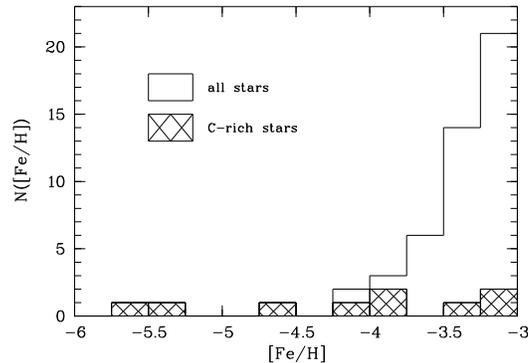


Figure 2. Low-metallicity tail of the observed halo metallicity distribution function. Only few objects are known, and many of the most iron-poor stars appear to be enriched with unusually large amounts of carbon. Figure adapted from Norris et al. (2007).

HE 0557–4840 (Norris et al. 2007) with $[\text{Fe}/\text{H}] < -4.8$ bridges the gap between $[\text{Fe}/\text{H}] = -4.0$ and the aforementioned two objects with $[\text{Fe}/\text{H}] < -5.0$. These extremely iron-deficient objects have opened a new, unique observational window of the time very shortly after the Big Bang. They provide key insight into the very beginning of the Galactic chemical evolution.

This review discusses the history of the first discoveries of metal-poor stars that laid the foundation to this field in § 2, and observed abundance trends at the lowest metallicities in § 3. § 4, § 5, and § 6 describe particular classes of metal-poor stars. The origins of metal-poor stars are reviewed in § 7 and the application of these stars to cosmological questions in § 8.

2. First Discoveries of Metal-Poor Stars

It was long believed that all stars would have a similar chemical composition to the Sun. In the late 1940s, however, some metal lines observed in stars appeared to be unusually weak compared with the Sun. It was first suspected that these stars could be hydrogen-deficient or might have peculiar atmospheres, but Chamberlain & Aller (1951) concluded that “one possibly undesirable factor” in their interpretation would be the “prediction of abnormally small amounts of Ca and Fe” in these stars. They found about 1/20th of the solar Ca and Fe values. Subsequent works on such metal-weak stars during the following few decades confirmed that stars do indeed have different metallicities that reflect different stages of the chemical evolution undergone by the Galaxy. HD140283 was one object observed by Chamberlain & Aller (1951). Repeated studies in the past half century have shown that this subgiant has $[\text{Fe}/\text{H}] \sim -2.5$ (e.g., Ryan et al. 1996). HD140283 is what one could call a “classical” metal-poor halo star that now often serves as reference star in chemical abundance analyses.

In 1981, Bond (1981) asked the question “Where is Population III?” At the time, Population III stars were suggested to be stars with $[\text{Fe}/\text{H}] < -3.0$

because no stars were known with metallicities lower than 1/1000 of the solar iron abundance. Even at $[\text{Fe}/\text{H}] \sim -3.0$, only extremely few objects were known although more were predicted to exist by a simple model of chemical evolution in the Galactic halo. Bond (1981) reported on unsuccessful searches for these Population III stars and concluded that long-lived low-mass star could not easily form from zero-metallicity gas, and hence were extremely rare, if not altogether absent. Today, we know that star formation in zero-metallicity gas indeed does not favor the creation of low-mass stars due to insufficient cooling processes (Bromm et al. 2002). It has also become apparent that the number of stars at the tail of the MDF is extremely sparsely populated (Figure 2). All those stars are fainter, and hence further away, than those among which Bond was searching ($B = 10.5$ to 11.5). As will be shown in this review, the current lowest metallicity has well surpassed $[\text{Fe}/\text{H}] \sim -3.0$ although it is still unclear what the lowest observable metallicity of halo stars may be.

A few years later, a star was serendipitously discovered, CD -38° 245, with a record low Fe abundance of $[\text{Fe}/\text{H}] = -4.5$ Bessell & Norris (1984). It was even speculated that CD -38° 245 might be a true Population III star, although Bessell & Norris (1984) concluded an extreme Population II nature for the star. The red giant was later reanalyzed and found to have $[\text{Fe}/\text{H}] = -4.0$ (Norris et al. 2001). CD -38° 245 stayed the lowest metallicity star for almost 20 years.

Large objective-prism surveys were carried out since the 1980s to systematically identify metal-poor stars. For a review on surveys and search techniques, the reader is referred to Beers & Christlieb (2005) and Christlieb (2006).

3. Abundance Trends at Low Metallicity

The quest to find more of the most metal-poor stars to investigate the formation of the Galaxy led to the first larger samples with metallicities down to $[\text{Fe}/\text{H}] \sim -4.0$. Abundance ratios $[\text{X}/\text{Fe}]$ as a function of $[\text{Fe}/\text{H}]$ were extended to low metallicities for the lighter elements ($Z < 30$) and neutron-capture elements ($Z > 56$). McWilliam et al. (1995) studied 33 stars with $-4.0 < [\text{Fe}/\text{H}] < -2.0$. The α -elements Mg, Si, Ca, and Ti are enhanced by ~ 0.4 dex with respect to Fe. α -elements are produced through α -capture during various burning stages of late stellar evolution, before and during supernova explosions. This enhancement is found down to the lowest metallicities, although with some exceptions. Recently, some stars were discovered that are α -poor (Carney et al. 1997; Ivans et al. 2003), whereas others are strongly overabundant in Mg and Si (Aoki et al. 2002). The iron-peak elements are produced during supernova type II explosions and their yields depend on the explosion energy. The abundance ratios of Cr/Fe and Mn/Fe become more underabundant with decreasing $[\text{Fe}/\text{H}]$ and below $[\text{Fe}/\text{H}] = -2.5$, down to ~ -0.7 at $[\text{Fe}/\text{H}] \sim -3.5$ for Cr and ~ -1.0 for Mn. Co becomes overabundant, up to ~ 0.8 . Sc/Fe and Ni/Fe have a roughly solar ratio, even at $[\text{Fe}/\text{H}] \sim -4.0$. Compared with these elements, the neutron-capture elements appear to behave differently. Sr has an extremely large scatter (~ 2 dex), indicating that different nucleosynthetic process may contribute to its Galactic inventory. Ba has less but still significant scatter at various metallicities. These abundance trends were also found by Ryan et al. (1996) who used 22 stars in the same metallicity

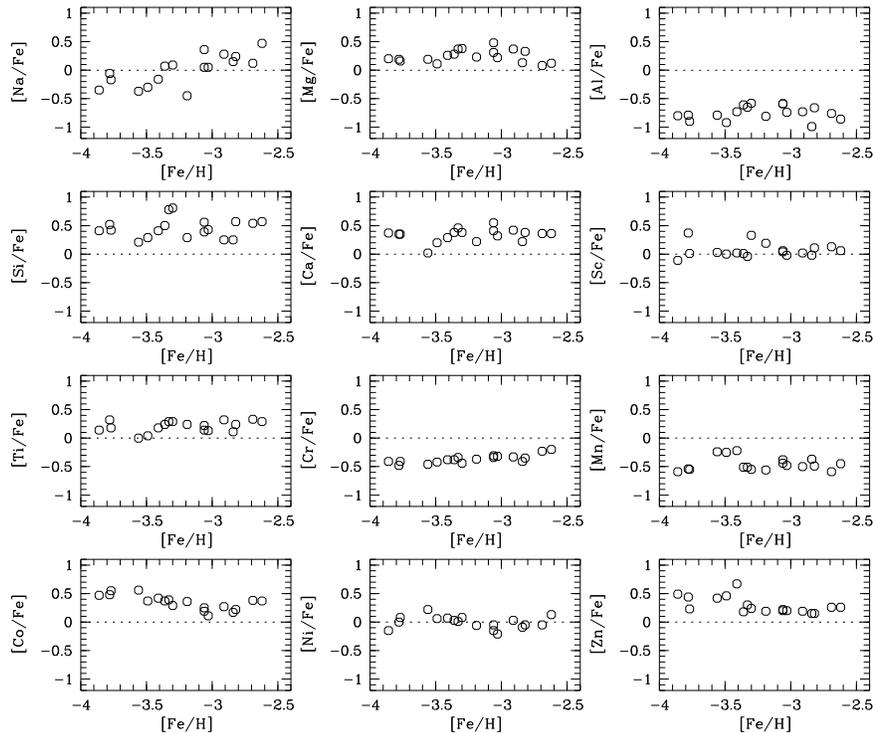


Figure 3. Abundance trends at the lowest metallicities by means of the Cayrel et al. (2004) stars.

regime. These authors furthermore proposed that the chemical enrichment of the early interstellar medium was primarily due to the explosion energies of the first supernovae that determine their yield distribution.

Several stars at the lowest metallicities showed significant deviations from the general trends. This level of abundance scatter at the lowest metallicities led to the conclusion that the interstellar medium was still inhomogeneous and not well mixed at $[\text{Fe}/\text{H}] \sim -3.0$ (e.g., Argast et al. 2000).

The claim for an inhomogeneous interstellar medium was diminished when Cayrel et al. (2004) presented a sample of 35 extremely metal-poor stars. Figure 3 show the abundance trends for those stars for 12 different elements. These authors found very little scatter in the abundance trends of elements with $Z < 30$ among their stars down to $[\text{Fe}/\text{H}] \sim -4.0$. This result suggested that the interstellar medium was already well-mixed at these early time leading to the formation of stars with almost identical abundance patterns.

4. r-Process Stars

All elements except H and He are created in stars during stellar evolution and supernova explosions. The so-called r-process stars formed from material previously enriched with heavy neutron-capture elements. About 5% of stars with

$[\text{Fe}/\text{H}] < -2.5$ contain a strong enhancement of neutron-capture elements associated with the rapid (r-) nucleosynthesis process (Beers & Christlieb 2005) that is responsible for the production of the heaviest elements in the Universe. In those stars we can observe the majority (i.e., ~ 70 of 94) of elements in the periodic table: the light, α , iron-peak, and light and heavy neutron-capture elements. So far, the nucleosynthesis site of the r-process has not yet unambiguously been identified, but supernova explosions are the most promising location. In 1995, the first r-process star was discovered, CS 22892-052 (McWilliam et al. 1995; Sneden et al. 1996). The heavy neutron-capture elements observed in this star follow the scaled solar r-process pattern. The abundance patterns of the heaviest elements with $56 < Z < 90$ of the few known r-process stars indeed *all* follow the scaled *solar* r-process pattern as can be seen in Figure 4. This behavior suggests that the r-process is universal – an important empirical finding that could not be obtained from any laboratory on earth. However, there are deviations among the lighter neutron-capture elements. Since it is not clear if the stellar abundance patterns are produced by a single r-process only, an additional new process might need to be invoked in order to explain all neutron-capture abundances (e.g., Aoki et al. 2005).

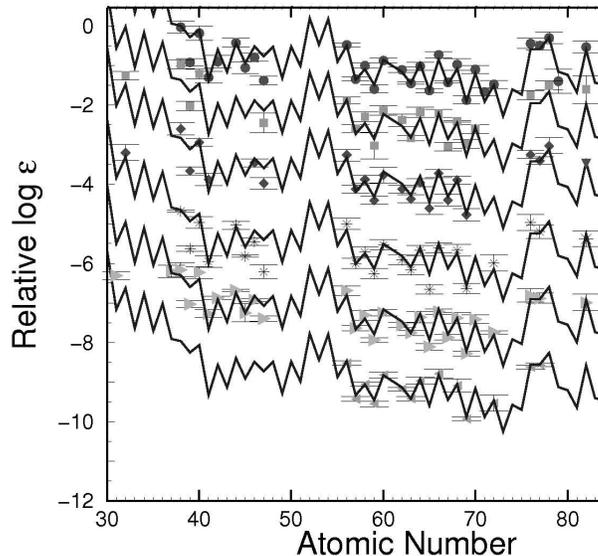


Figure 4. r-process abundance patterns of the most strongly-enhanced r-process metal-poor stars (various symbols). Overplotted are scaled solar r-process patterns. There is excellent agreement between the stellar data and the solar r-process pattern. All patterns are arbitrarily offset to allow a visual comparison. Figure kindly provided by J. J. Cowan.

Among the heaviest elements are the long-lived radioactive isotopes ^{232}Th (half-life 14 Gyr) and ^{238}U (4.5 Gyr). While Th is often detectable in r-process stars, U poses a real challenge because *only one*, extremely weak, line is available in the optical spectrum. By comparing the abundances of the radioactive Th and/or U with those of stable r-process nuclei, such as Eu, stellar ages can be

Table 1. Stellar ages derived from different abundance ratios

Star	Age (Gyr)	Abundance ratio	Ref.
HD15444	15.6 ± 4	Th/Eu	Cowan et al. (1999)
CS31082-001	14.0 ± 2	U/Th	Hill et al. (2002)
BD +17° 3248	13.8 ± 4	average of several	Cowan et al. (2002)
CS22892-052	14.2 ± 3	average of several	Snedden et al. (2003)
HD221170	11.7 ± 3	Th/Eu	Ivans et al. (2006)
HE 1523–0901	13.2 ± 2	average of several	Frebel et al. (2007a)

derived. Through individual age measurements, r-process objects become vital probes for observational “near-field” cosmology by providing an independent lower limit for the age of the Universe. This fortuitously also provides the opportunity of bringing together astrophysics and nuclear physics because these objects act as a “cosmic lab” for both fields of study.

Most suitable for such age measurements are cool metal-poor giants that exhibit strong overabundances of r-process elements¹. Since CS 22892-052 is very C-rich, the U line is blended and not detectable. Only the Th/Eu ratio could be employed, and an age of 14 Gyr was derived (Snedden et al. 2003). The U/Th chronometer was first measured in the giant CS 31082-001 (Cayrel et al. 2001), yielding an age of 14 Gyr. The recently discovered giant HE 1523–0901 ($[\text{Fe}/\text{H}] = -3.0$; Frebel et al. 2007a) has the largest measured overabundance of r-process elements. It is only the *third* star with a U detection at all, and is has the most reliable measurement of all three. HE 1523–0901 is the first star that has been dated with seven different “cosmic clocks”, i.e. abundance ratios such as U/Th, Th/Eu, U/Os. The average age obtained is 13 Gyr, which is consistent with the WMAP (Spergel et al. 2007) age of the Universe of 13.7 Gyr. These age measurements also confirm the old age of similarly metal-poor stars. Table 1 lists the ages derived from the Th/Eu and other abundance ratios measured in the stars that are shown in Figure 4. Age uncertainties, arising in large parts from systematic uncertainties, are also given.

Since Eu and Th are much easier to detect than U, the Th/Eu chronometer has been used several times to derive stellar ages of metal-poor stars. Compared to Th/Eu, the Th/U ratio is much more robust to uncertainties in the theoretically derived production ratio due to the similar atomic masses of Th and U (Wanajo et al. 2002). Hence, stars displaying Th *and* U are the most desired stellar chronometers.

5. Carbon-Rich Stars & s-Rich Stars

It was noted by Rossi et al. (1999) that a large fraction of metal-poor stars has an overabundance of carbon with respect to iron ($\text{C}/\text{Fe} > 1.0$). This suggestion has been widely confirmed by now, although different samples led to a range

¹Stars with $[\text{r}/\text{Fe}] > 1.0$; r represents the average abundance of elements associated with the r-process.

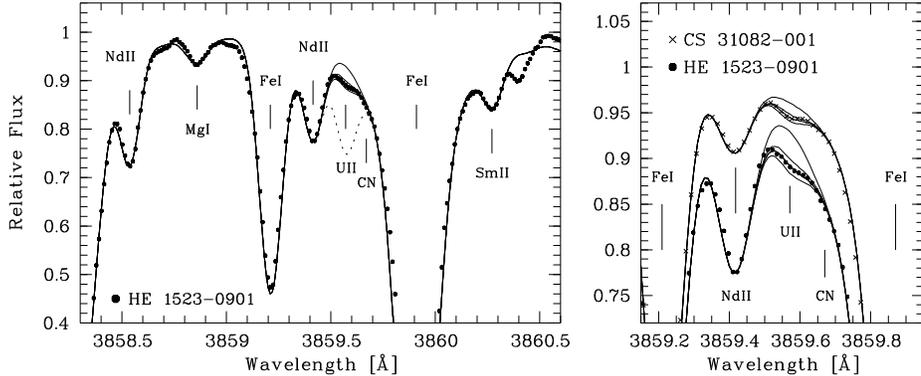


Figure 5. Spectral region around the U II line in HE 1523–0901 (*filled dots*) and CS 31082–001 (*crosses*; right panel only). Overplotted are synthetic spectra with different U abundances. The dotted line in the left panel corresponds to a scaled solar r-process U abundance present in the star if no U were decayed. Figure taken from Frebel et al. (2007a).

of fractions (10% to 25%; e.g., (Cohen et al. 2005; Lucatello et al. 2006)). At the lowest metallicities, this fraction is even higher, and all three stars with $[\text{Fe}/\text{H}] < -4.0$ are extremely C-rich. The fraction of C-rich stars may also increase with increasing distance from the Galactic plane (Frebel et al. 2006b).

Many C-rich stars also show an enhancement in neutron-capture elements. These elements are produced in the interiors of intermediate-mass asymptotic giant branch (AGB) stars through the slow (s-) neutron-capture process. Such material is later dredged up to the star’s surface. Contrary to the r-process, the s-process is not universal because two different sites seem to host s-process nucleosynthesis. The so-called “weak” component occurs in the burning cores of the more massive stars, and preferentially produces elements around $Z \sim 40$. The “main” component of the s-process occurs in the helium shells of thermally pulsing lower mass AGB stars and is believed to account for elements with $Z \geq 40$ (e.g., Arlandini et al. 1999). The s-process leads to a different characteristic abundance pattern than the r-process. Indeed, the s-process signature is observed in some metal-poor stars, and their neutron-capture abundances follow the scaled solar s-process pattern. The metal-poor objects observed today received the s-process enriched material during a mass transfer event across a binary system from their more massive companion that went through the AGB phase (e.g., Norris et al. 1997a; Aoki et al. 2001). The binary nature of many s-process stars has been confirmed through monitoring their radial velocity variations (Lucatello et al. 2005). Some of the s-process metal-poor stars contain huge amounts of lead (Pb) – in fact they are more enhanced in lead than in any other element heavier than iron (Van Eck et al. 2001). Pb is the end product of neutron-capture nucleosynthesis and AGB models predict a significant Pb, and also Bi, production (Gallino et al. 1998). More generally, the observed patterns of many s-process metal-poor stars can be reproduced with these AGB models, which is evidence for a solid theoretical understanding of AGB nucleosynthesis. Unlike the r-process, it is not clear whether the s-process already operated in the

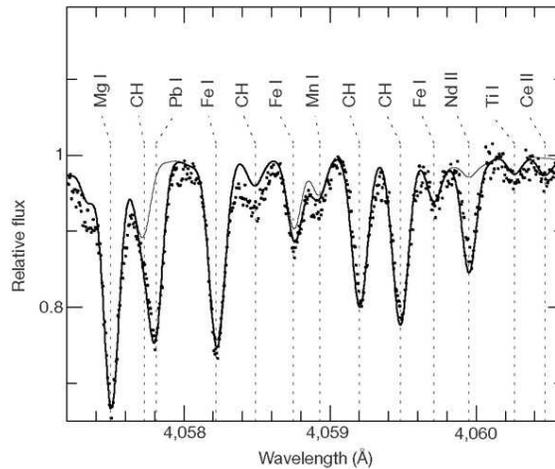


Figure 6. Spectral region around the Pb I line at $\sim 4058 \text{ \AA}$ in the metal-poor star HD196944 (dots). Overplotted is the best-fit synthetic spectrum. Figure taken from Van Eck et al. (2001).

early Universe, since it depends on the presence of seed nuclei (i.e., from Fe-peak elements created in previous generations of stars) in the host AGB star. However, there is recent evidence from some metal-poor stars (Simmerer et al. 2004) that may challenge the late occurrence of the s-process at higher metallicities.

As usual, there are exceptions. Some C-rich stars do not show any s-process enrichment (Norris et al. 1997b; Frebel et al. 2007c), and the origin of these chemical signatures remains unclear. Other C-rich stars show r-process enhancement (Snedden et al. 1996), and the two stars with the largest carbon overabundances with respect to iron are the two with $[\text{Fe}/\text{H}] < -5.0$. The frequent finding of C-rich stars in combination with a variety of abundance patterns points towards the importance of C in the early Universe. The exact role of C is still unclear but it likely played a crucial role in star formation processes (Bromm & Loeb 2003).

6. $[\text{Fe}/\text{H}] < -5.0$ Stars

In 2002, the first star with a new, record-low iron abundance was found. The faint ($V = 15.2$) red giant HE 0107–5240 has $[\text{Fe}/\text{H}] = -5.3$ (Christlieb et al. 2002)². In 2004, the bright ($V = 13.5$) subgiant HE 1327–2326 was discovered (Frebel et al. 2005; Aoki et al. 2006). Both objects were discovered in the Hamburg/ESO survey. HE 1327–2327 had an even lower iron abundance of $[\text{Fe}/\text{H}] = -5.4$. This value corresponds to $\sim 1/250,000$ of the solar iron abun-

²Applying the same non-LTE correction to the FeI abundances of HE 0107–5240 and HE 1327–2326 leads to a final abundance of $[\text{Fe}/\text{H}] = -5.2$ for HE 0107–5240.

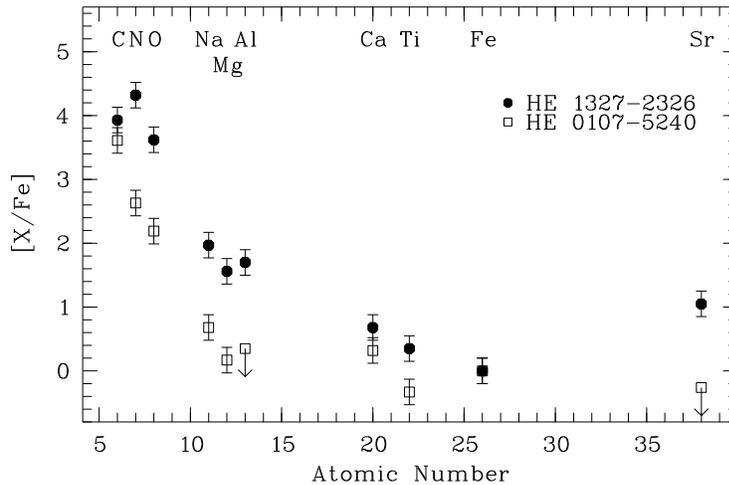


Figure 7. Abundance patterns of HE 0107–5240 and HE 1327–2326. Abundances taken from Christlieb et al. (2004), Bessell et al. (2004), Frebel et al. (2005), and Frebel et al. (2006a), where the LTE Fe abundance of HE 0107–5240 was corrected for non-LTE effects in the same way as for HE 1327–2326.

dance. With its extremely large abundances of CNO elements, HE 1327–2326 has a very similar abundance pattern compared with HE 0107–5240 (see Figure 7). No neutron-capture element is found in HE 0107–5240, whereas, unexpectedly, Sr is observed in HE 1327–2326. The Sr may originate from the neutrino-induced νp -process operating in supernova explosions (Fröhlich et al. 2006). Furthermore, in the relatively unevolved subgiant HE 1327–2326 Li could not be detected, $\log \epsilon(\text{Li}) < 1.6$, where $\log \epsilon(A) = \log_{10}(N_A/N_H) + 12$. This is surprising, given that the primordial Li abundance is often inferred from similarly unevolved metal-poor stars (Ryan et al. 1999). The upper limit found from HE 1327–2326, however, strongly contradicts the WMAP value ($\log \epsilon(\text{Li}) = 2.6$) from the baryon-to-photon ratio (Spergel et al. 2007). This indicates that the star must have formed from extremely Li-poor material. Figure 8 shows the C and Mg abundance for the two stars in comparison with other, more metal-rich stars. Whereas both $[\text{Fe}/\text{H}] < -5.0$ objects have similarly high C abundances that are much higher than C/Fe ratios observed in other stars, there exists a significant difference in the Mg abundances. HE 0107–5240 has an almost solar Mg/Fe ratio similar to the other stars. An elevated Mg level is, however, observed not only in HE 1327–2326, but also in a few stars at higher metallicities.

If HE 1327–2327 would have been a few hundred degrees hotter or a few tenths of a dex more metal-poor, no Fe lines would have been detectable in the spectrum. Even now, the strongest Fe lines are barely detectable and very high S/N ratio (> 100) data were required for the successful Fe measurement. The hunt for the most metal-poor stars with the lowest iron abundances is thus reaching its technical limit with regard to turn-off stars. Fortunately, in suitable giants, Fe lines should be detectable at even lower Fe abundances than $[\text{Fe}/\text{H}] <$

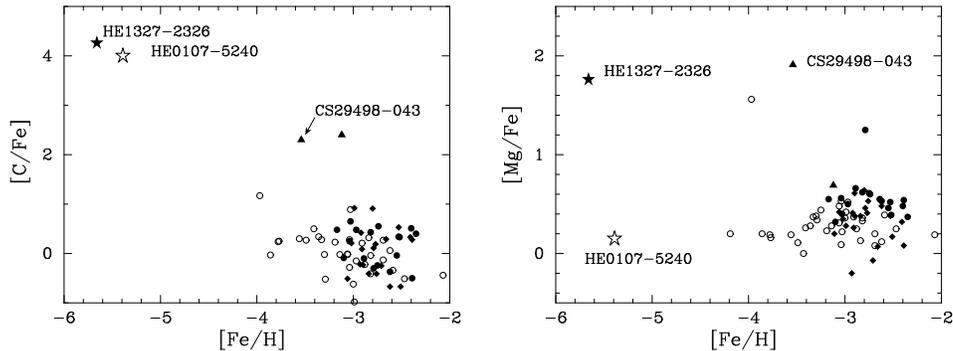


Figure 8. C/Fe and Mg/Fe abundance ratios as function of $[\text{Fe}/\text{H}]$. See Aoki et al. (2006) for full references.

–5.5. It remains to be seen, though, what the lowest iron-abundance, or lowest overall metallicity for that matter, in a stellar object might be. Considering a simple accretion model, (Iben 1983) suggested such the observable lower limit to be $[\text{Fe}/\text{H}] < -5.7$. Future observations may be able to reveal such a lower limit.

HE 0107–5240 and HE 1327–2326 immediately became benchmark objects to constrain various theoretical studies of the early Universe, such as the formation of the first stars (e.g., Yoshida et al. 2006), the chemical evolution of the early interstellar medium (e.g., Karlsson & Gustafsson 2005) or supernovae yields studies. More such stars with similarly low metallicities are urgently needed. Very recently, a star was found at $[\text{Fe}/\text{H}] < -4.75$ (Norris et al. 2007). It sits right in the previously claimed “metallicity gap” between the stars at $[\text{Fe}/\text{H}] \sim -4.0$ and the two with $[\text{Fe}/\text{H}] < -5.0$. These three stars provide crucial information for the shape of the tail of the metallicity distribution function.

7. What is the Chemical Origin of the Most Metal-Poor Stars?

The two known hyper-metal-poor stars (with $[\text{Fe}/\text{H}] < -5.0$; Christlieb et al. 2002; Frebel et al. 2005) provide a new observational window to study the onset of the chemical evolution of the Galaxy. The *highly individual* abundance patterns of these and other metal-poor stars have been successfully reproduced by several supernovae scenarios. HE 0107–5240 and HE 1327–2326 both appear to be early, extreme Population II stars possibly displaying the “fingerprint” of only one Population III supernova. Umeda & Nomoto (2003) first reproduced the observed abundance pattern of HE 0107–5240 by suggesting the star formed from material enriched by a faint $25 M_{\odot}$ supernova that underwent a mixing and fallback process. To achieve a simultaneous enrichment of a lot of C and only little Fe, large parts of the Fe-rich yield fall back onto the newly created black hole. Using yields from a supernova with similar explosion energy and mass cut, Iwamoto et al. (2005) then explained the origin of HE 1327–2326.

Meynet et al. (2006) explored the influence of stellar rotation on elemental yields of very low-metallicity supernovae. The stellar mass loss yields of fast

rotating massive Pop III stars quantitatively reproduce the CNO abundances observed in HE 1327–2326 and other metal-poor stars. Limongi et al. (2003) were able to reproduce the abundances of HE 0107–5240 through pollution of the birth cloud by at least two supernovae. Suda et al. (2004) proposed that the abundances of HE 0107–5240 would originate from a mass transfer of CNO elements from a postulated companion, and from accretion of heavy elements from the interstellar medium. However, neither for HE 0107–5240 nor HE 1327–2326 show radial velocity variations, that would indicate binarity. Self-enrichment with CNO elements has also been ruled out for HE 0107–5240 (Picardi et al. 2004), while this is not a concern for the less evolved subgiant HE 1327–2326.

Tominaga et al. (2007) model the averaged abundance pattern of four non-carbon-enriched stars with $-4.2 < [\text{Fe}/\text{H}] < -3.5$ (Cayrel et al. 2004) with the elemental yields of a massive, energetic ($\sim 30 - 50 M_{\odot}$) Population III hypernova. Abundance patterns of stars with $[\text{Fe}/\text{H}] \sim -2.5$ can be reproduced with integrated (over a Salpeter IMF) yields of normal Population III supernovae.

8. Stellar Archaeology

Numerical simulations show that the first stars in the Universe must have been very massive ($\sim 100 M_{\odot}$). On the other hand, the observed metal-poor stars all have *low masses* ($< 1 M_{\odot}$). To constrain the first low-mass star formation, Bromm & Loeb (2003) put forward their theory that fine-structure line cooling by C and O nuclei, as provided by the Population III objects, may be responsible for the necessary cooling of the interstellar medium to allow low-mass stars to form. On the other hand, cooling by dust may play a major role in the transition from Population III to Population II star formation. Dust grains created during the first supernova explosions may induce cooling and subsequent fragmentation processes that lead to the formation of subsolar-mass stars (e.g., Schneider et al. 2006).

Such cooling theories can be tested with large numbers of *carbon and oxygen-poor* metal-poor stars. In order to form, a critical metallicity of the interstellar medium is required. Metal-poor stars with the lowest metallicities should thus have values equal to or higher than the critical metallicity. Suitable metallicity indicators for the fine-structure line theory are C and O abundances in the most metal-poor stars. Frebel et al. (2007b) collected observational literature data of these two abundances in metal-poor stars. A critical metallicity limit of $D_{\text{trans}} = -3.5$ was developed, where D_{trans} parameterizes the observed C and/or O abundances. So far, no star has abundances below the critical value, as can be seen in Figure 9. It is predicted that any future stars to be discovered with $[\text{Fe}/\text{H}] < -4$ should have high C and/or O abundances. This agrees with the empirically frequent C-richness amongst the most metal-poor stars. Since the critical metallicity of the dust cooling theory is a few orders of magnitude below the D_{trans} the current data is also consistent with that theory, although less firm constraints can be derived at this point. Future observations of large numbers of metal-poor stars will provide the necessary constraints that may lead to identify the dominant cooling process responsible for low-mass star formation in the early Universe.

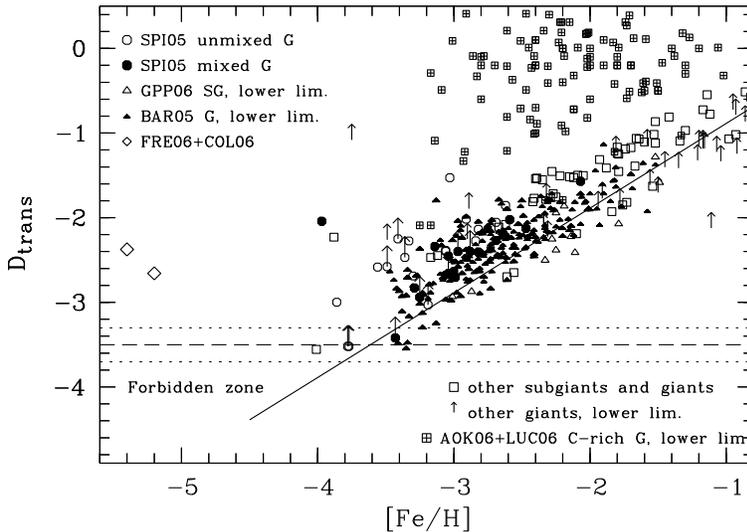


Figure 9. Comparison of metal-poor data with the theory that fine-structure lines of C and O dominate the transition from Population III to Population II in the early Universe. C- and O-poor extremely metal-poor stars are invaluable to test this formation scenario. Figure taken from Frebel et al. (2007b).

9. Outlook

Many more metal-poor stars are being discovered these days, thanks to recent and ongoing large-scale surveys. The hunt for the most metal-poor stars has certainly just begun with the discoveries of the two stars with $[\text{Fe}/\text{H}] < -5.0$. Exciting times are ahead which will hopefully lead to observations of new metal-poor stars from which we can learn about the first stars, the onset of the Galactic chemical enrichment and the involved nucleosynthesis processes. More stars at the lowest metallicities are clearly desired in this quest and the next-generation telescopes will certainly be of great interest to this field. There are ongoing targeted searches for the most metal-poor stars with existing 8-10m optical facilities. Large high-resolution spectroscopy programs have been started with the Hobby-Eberly Telescope, *Chemical Abundance of Stars in the Halo* (CASH), and also with Subaru, Keck and Magellan. More faint stars (down to $V \sim 17$) are currently being discovered with surveys such as SDSS and SDSS/SEGUE. However, many stars are too faint to be followed-up with high S/N spectroscopy with the current 8-10m telescopes. Future 25 m class telescopes, such as the Giant Magellan Telescope, will be required for discovering the most metal-poor stars in the outskirts of the Galactic halo and nearby dwarf galaxies.

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