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Stellar Archaeology: New Science with Old Stars

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The abundance patterns of metal-poor stars provide us a wealth of chemical information about various stages of cosmic chemical evolution. 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 nature and condition of the early Universe, and the associated processes of early star- and galaxy formation. This proceeding summarizes the astrophysical topics and questions that can be addressed with metal-poor stars. For the full version of the review, the reader is referred to Frebel 2010.

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1. Introduction

After the Big Bang, the first stars that formed from the pristine gas were very massive, of the order of 100 $M_\odot$ (e.g., Bromm et al. 2001; Yoshida et al. 2008). After a very short life time these co-called Population III stars exploded as supernovae, which then provided the first metals to the still primordial interstellar medium. All subsequent generations of stars, Pop II, formed from chemically enriched material. The most metal-poor stars are the earliest and most extreme Population II objects and belong to the stellar generations that formed from the non-zero metallicity gas left behind by the first stars.

In their atmospheres these old objects preserve details of the chemical composition of their birth gas cloud. They thus provide stellar archaeological evidence of the earliest times of the Universe. In particular, the chemical abundance patterns provide information about the formation and evolution of the elements and the involved nucleosynthesis processes and sites. By extension, metal-poor stars provide constraints on the nature of the first stars, the initial mass function, and the chemical yields of first/early SNe. This knowledge is invaluable for our understanding of the cosmic chemical evolution and the onset of star- and galaxy formation processes including the formation of the galactic halo. In summary, galactic metal-poor stars are the local equivalent of the high-redshift Universe, enabling observational constraints on the nature of the first stars and supernovae, and more generally, on various theoretical works on the early Universe.

Due to their low masses ($\sim 0.8\,M_\odot$) metal-poor stars have extremely long lifetimes that exceed the current age of the Universe of ~ 14 Gyr (Spergel et al., 2007). Hence, these stellar "fossils" of the early Universe are still observable. However, the most metal-poor stars (e.g., stars with[1] [Fe/H] < -5.0; Frebel et al. 2005) are extremely rare (Schörck et al., 2009), and hence difficult to identify. The most promising way forward is to survey large volumes far out into the Galactic halo. Past surveys include the HK survey and the Hamburg/ESO survey (Beers & Christlieb, 2005) which have been very successful in producing large samples of extremely metal-poor stars (with [Fe/H] < -3.0). It was also shown that there are many different types of abundance patterns that arise as the result of specific nucleosynthesis processes. The fact that the nuclear physics details of these processes can be probed with the help of stars, means that stellar astrophysics becomes "nuclear astrophysics". This is a very complementary approach to experimental nuclear physics that is often limited in its attempts to create the most exotic nuclei or extreme processes, like the r-process, in the laboratory.

Over the past few years, a number of extensive reviews have been published on the various roles and applications of metal-poor stars to different astrophysical topics. Beers & Christlieb (2005) report on the discovery history, search techniques and results, and the different abundance "classes" of metal-poor stars. Sneden et al. (2008) reviewed the evolution of neutron-capture elements in the Galaxy, including the s- and r-process stars. Recent advances regarding the stellar contents of different types of dwarf galaxies are presented in Tolstoy et al. (2009) and Koch (2009). Finally, Frebel (2010) summarized the role of metal-poor stars in the cosmological context, and how early star- and galaxy evolution can be studied with them. This proceeding is based on Frebel

[1]The main indicator used to determine stellar metallicity is the iron abundance, [Fe/H], which is defined as [A/B]= $\log_{10}(N_A/N_B)_\star - \log_{10}(N_A/N_B)_\odot$ for the number N of atoms of elements A and B, and $\odot$ refers to the Sun. With few exceptions, [Fe/H] traces the overall metallicity of the objects fairly well.

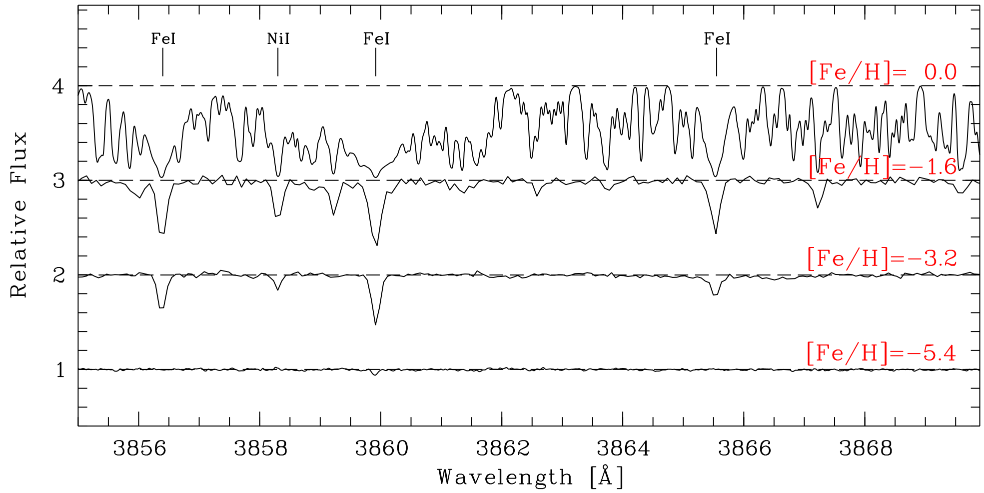

Figure 1: Spectral comparison of stars in the main-sequence turn-off region with different metallicities. Several atomic absorption lines are marked. The variations in line strength reflect the different metallicities. From top to bottom: Sun with [Fe/H] = 0.0, G66-30 with [Fe/H] = −1.6 (Norris et al., 1997), G64-12 with [Fe/H] = −3.2 (Aoki et al., 2006), and HE1327-2326 with [Fe/H] = −5.4 (Frebel et al., 2005). Reproduced from Frebel (2010).

(2010), and thus only briefly summarizes a few specific aspects of what is described in more detail in the above review.

2. The Most Metal-Poor Stars

The first star with a record-low iron abundance was found in 2001. The faint ($V = 15.2$) red giant HE 0107−5240 has [Fe/H] = −5.2 (Christlieb et al., 2002). In 2004, the bright ($V = 13.5$) subgiant HE 1327−2326 was discovered (Frebel et al., 2005; Aoki et al., 2006). HE 1327−2327 has an even lower iron abundance of [Fe/H] = −5.4. This value corresponds to $\sim 1/250,000$ of the solar iron abundance. Interestingly, the entire mass of iron in HE 1327−2326 is actually 100 times less than that in the Earth's core. A third star with [Fe/H] = −4.75 (Norris et al., 2007) was found in 2006. The metallicity of the giant HE 0557−4840 is in between the two [Fe/H] < -5.0 stars and the next most metal-poor stars are [Fe/H] ~ -4.2. Hence it sits right in the previously claimed "metallicity gap" (between [Fe/H] ~ -4.0 and [Fe/H] ~ -5.0; e.g. Shigeyama et al. 2003) showing that the scarcity of stars below [Fe/H] ~ -4.2 has no physical cause but is merely an observational incompleteness. All three objects were found in the Hamburg/ESO survey (Frebel et al., 2006; Christlieb et al., 2008) making it the so far most successful database for metal-poor stars.

The most striking features in both [Fe/H] < -5.0 stars are the extremely large overabundances of CNO elements ([C,N,O/Fe] ~ 2 to 4). HE 0557−4840 partly shares this signature by also having a fairly large [C/Fe] ratio. Other elemental ratios [X/Fe] are somewhat enhanced in HE 1327−2327 with respect to the stars with $-4.0 <$ [Fe/H] < -2.5, but less so for the two giants. No neutron-capture element is detected in HE 0107−5240 or HE 0557−4840, whereas, unexpectedly, Sr is observed in HE 1327−2326. Despite expectations, Li could not be detected

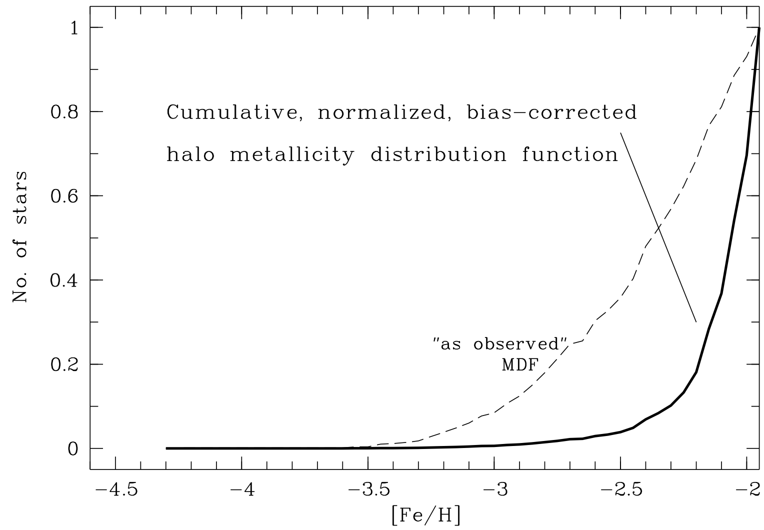

Figure 2: Metallicity distribution function of metal-poor halo stars. Data taken from Schörck et al. (2009). The dashed line shows the "as observed" function which reflects the distribution of stars discovered in the Hamburg/ESO survey. The solid line represents the corrected function reflecting the actual underlying population of metal-poor stars.

in the relatively unevolved subgiant HE 1327−2326. The upper limit is $\log\varepsilon(\mathrm{Li}) < 0.6$, where $\log\varepsilon(\mathrm{A}) = \log_{10}(N_{\mathrm{A}}/N_{\mathrm{H}}) + 12$. This is surprising, given that the primordial Li abundance is often inferred from similarly unevolved metal-poor stars (Ryan et al., 1999). Furthermore, the upper limit found from HE 1327−2326, however, strongly contradicts the WMAP value ($\log\varepsilon(\mathrm{Li}) = 2.6$) from the baryon-to-photon ratio (Spergel et al., 2007). This may indicates that the star formed from extremely Li-poor material.

HE 0107−5240 and HE 1327−2326 immediately became benchmark objects to constrain various theoretical studies of the early Universe, such as calculations of Pop III SN yields. Their highly individual abundance patterns have been successfully reproduced by several different SNe scenarios. This makes HE 0107−5240 and HE 1327−2326 early, extreme Pop II stars that possibly display the "fingerprint" of just one Pop III SN. Umeda & Nomoto (2003) first matched the yields of a faint 25 $M_{\odot}$ SN that underwent a mixing and fallback process to the observed abundances of HE 0107−5240. To achieve a simultaneous enrichment of a lot of C and only little Fe, large parts of the Fe-rich SN ejecta have to fall back onto the newly created black hole. Using yields from a SN with similar explosion energy and mass cut, Iwamoto et al. (2005) then reproduced the abundance pattern of HE 1327−2326 also. Trying to fit the observed stellar abundances, Heger & Woosley (2008) are employing an entire grid of Pop III SN yields to search for the best match to the data. A similar progenitor mass range as the Umeda & Nomoto (2003) 25 $M_{\odot}$ model was found to be the best match to have provided the elemental abundances to the ISM from which these Pop II stars formed. Meynet et al. (2006) explored the influence of stellar rotation on elemental yields of 60 $M_{\odot}$ near-zero-metallicity SNe. The stellar mass loss rate of rotating massive Pop III stars qualitatively reproduces the CNO abundances observed in HE 1327−2326 and other carbon-rich metal-poor stars.

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3. Nuclear Astrophysics with Metal-Poor Stars

About 5% of metal-poor stars with [Fe/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. These elements were not produced in the observed metal-poor star itself, but in a previous-generation supernova explosions. We are thus able to study the "chemical fingerprint" of individual supernova explosions that occurred just prior to the formation of the observed star. So far, however, the nucleosynthesis site of the r-process has not yet unambiguously been identified, but supernovae with progenitor stars of $8-10\,M_{\odot}$ are the most promising locations Qian & Wasserburg (2003).

The giant HE 1523$-$0901 ($V = 11.1$) was found in a sample of bright metal-poor stars (Frebel et al., 2006) from the Hamburg/ESO Survey. It has the so far strongest enhancement in neutron-capture elements associated with the r-process, [r/Fe] $= 1.8$. Its metallicity is [Fe/H] $= -3.0$ (Frebel et al., 2007a). The spectrum of HE 1523$-$0901 shows numerous strong lines of ~ 25 neutron-capture elements, such as those of Sr, Ba, Eu, Os, and Ir. A full discussion of the complete abundance analysis will be given elsewhere (A. Frebel et al. 2011, in preparation). This makes possible a detailed study of the nucleosynthesis products of the r-process. This fortuitously also provides the opportunity of bringing together astrophysics and nuclear physics because these objects act as a "cosmic lab" for both fields of study. The radioactive elements Th and U could be detected in this star also (see the reviews of (Frebel, 2008; Sneden et al., 2008; Frebel, 2010)). Only three stars have measured U abundances, of which HE 1523$-$0901 has the most confidently determined value. From comparing the stable Eu, Os, and Ir abundances with measurements of Th and U, stellar ages can be derived. Based on seven such chronometer abundance ratios, the age of HE 1523$-$0901 was found to be ~ 13 Gyr.

Next to Th and U, knowing all three abundances of Th, U, and Pb provides a self-consistency test for r-process calculations. These three abundances are intimately coupled, not only with each other but also to the conditions (and potentially also the environment) of the r-process. Hence, constraints on the different models yielding different abundance distributions can be obtained by explaining the stellar triumvirate of the Th, U and Pb abundances. Such constraints lead to a better understanding of how and where r-process nucleosynthesis can occur. In turn, improved r-abundance calculations are crucial for reliably predicting the initial production ratios of Th/r, U/r and Th/U, which are an implicit necessity for more accurate age dating of r-process enhanced stars. Based on new UVES data, a Pb abundance could be determined for HE 1523$-$0901. The preliminary abundance is $\log\varepsilon(\mathrm{Pb}) \sim -0.35$. In summary, Pb is produced through several decay channels. At the time when the r-process event stops, there is the direct (β- and β-delayed neutron) decay of very neutron-rich isobaric nuclei with $A = 206-208$ to ^{206}Pb, ^{207}Pb, and ^{206}Pb. Then there is α- and β-decay of nuclei with $A \geq 210$ back to Pb and finally the radioactive decay of the Th and U isotopes back to Pb over the course of the age of the Universe. The initial abundances of Th and U are driven in the same way as Pb, i.e., by a direct channel of nuclei with $A = 232$, 235 and 238, and an indirect way from the decay of r-process nuclei with heavier masses. Of course, the Th and U abundances determine, in part, the Pb abundance. Taking all these details into account when

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modeling the r-process, the observed Pb abundances can be compared with model predictions. After 13 Gyr of decay, the prediction for the Th/U ratio by Frebel & Kratz (2009) agrees well abundance measurement. With this good level of agreement, HE 1523-0901 remains a vital probe for observational nuclear astrophysics, which r-process models can effectively be constrained.

4. Extremely Metal-Poor Stars in Dwarf Galaxies

Simulations of the hierarchical assembly of galaxies within the cold dark matter framework (Diemand et al. 2007; Springel et al. 2008) show that the Milky Way halo was successively built up from small dark matter substructures, often referred to as galactic building blocks. This hierarchical way of galaxy assembly had long been suggested by Searle & Zinn (1978). However, these simulations only include dark matter, and it remains unclear to what extent small dark halos contain luminous matter in the form of stars and gas. Studying the onset of star formation and associated chemical evolution in dwarf galaxies thus provides some of the currently missing information to our understanding of how the observed properties of small satellites relate to the dark matter substructures that build up larger galaxies. The connection between the surviving dwarfs and those that dissolved to form the halo is best addressed by examining in detail the stellar chemical compositions of present-day dwarf galaxies. Establishing detailed chemical histories of these different systems can provide constraints on their dominant chemical enrichment mechanisms and events, as well as the formation process of the Milky Way. Specifically, detailed knowledge of the most metal-poor (hence, oldest) stars in a given system allow insight into the earliest phases of star formation before the effects of internal chemical evolution were imprinted in stars born later with higher metallicity (see reviews by Tolstoy et al. 2009 and Koch 2009).

Assuming that the currently observable dwarf galaxies are analogs of early systems that were accreted to form the halo, they provide an opportunity to study this assembly history. Particularly, the metallicities of stars in dwarf galaxies must reach values as low as (or lower) than what is currently found in the Galactic halo, and the abundance ratio of those low-metallicity stars must be roughly equal to those of equivalent stars in the halo. In the "classical" dSph galaxies, higher-metallicity stars were found to have abundance ratios different from comparable halo stars. Most strikingly, the α-element abundances are not enhanced, indicating different enrichment mechanisms and timescales in these systems (e.g., Shetrone et al. 2003). But stars with [Fe/H] < -3 were recently discovered the classical dwarf galaxy Sculptor dSph (Kirby et al., 2009). A metallicity of [Fe/H] $= -3.8$ for one star was confirmed from the high-resolution spectrum taken with Magellan/MIKE (Frebel et al., 2010a). Additional, similar objects have also been found (Tafelmeyer et al., 2010). All their chemical abundances strongly resemble those of halo stars with [Fe/H] < -3.5.

The metallicity-luminosity relationship of dwarf galaxies indicates that the lowest luminosity dwarfs should contain extremely metal-poor stars. Kirby et al. (2008) identified 15 extremely metal-poor stars in the ultra-faint dwarfs, of which six were observed with high-resolution spectroscopy (three located in each Ursa Major II and Coma Berenices (Frebel et al., 2010b). Two of the stars in Ursa Major II are extremely metal-poor having metallicities of [Fe/H] < -3.0. Additional stars have been discovered in other ultra-faint dwarfs, in Segue and Bootes (Geha et al., 2009; Norris et al., 2010b, 2008), of which some have been analyzed with high-resolution spectroscopy

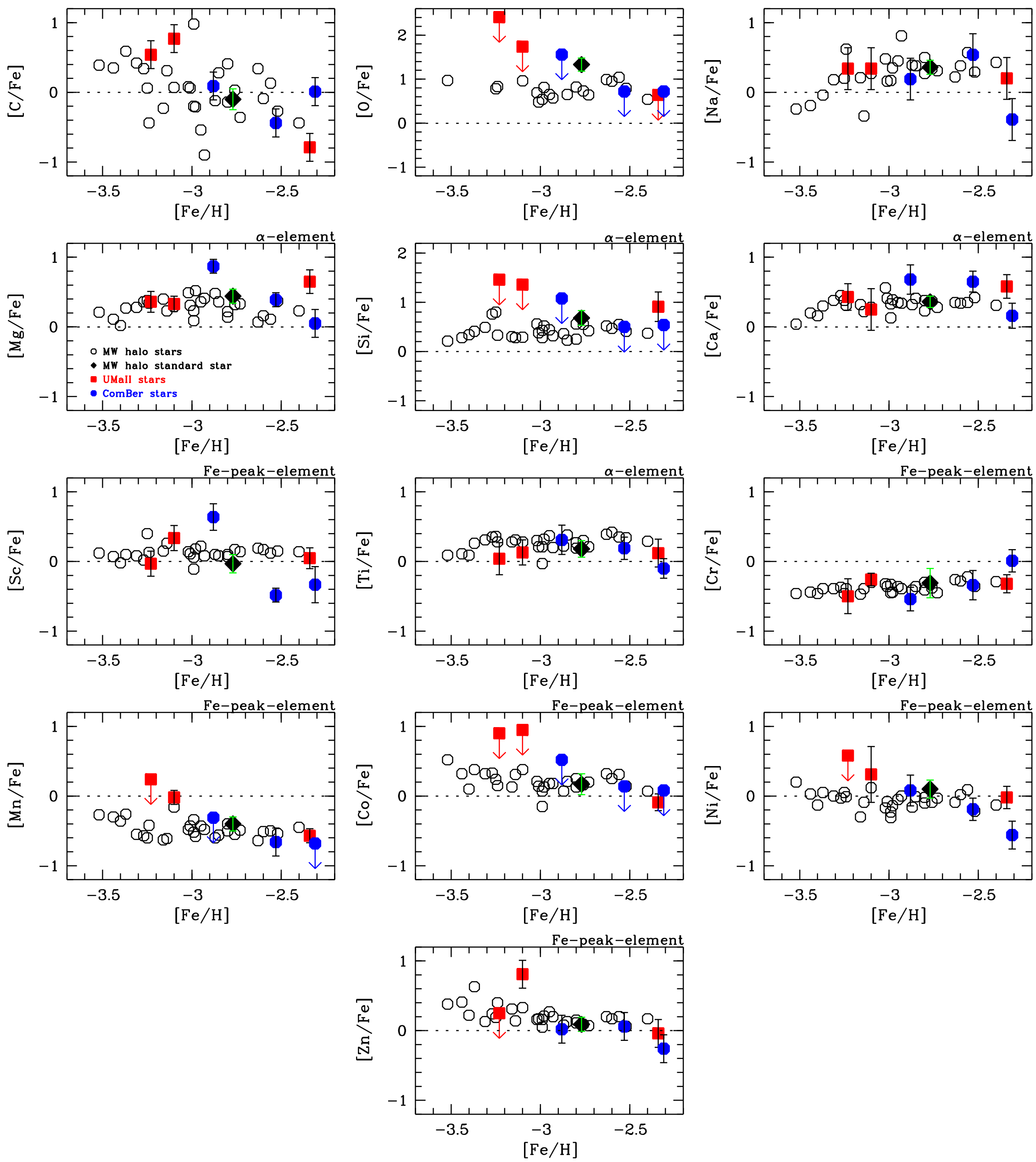

Figure 3: Abundances ([X/Fe]) of ultra-faint dwarf galaxy stars for light and iron-peak elements in comparison with those of halo stars (Cayrel et al., 2004) (*open black circles*). *Red squares* indicate UMa II stars, *blue circles* show ComBer stars. HD 122563, a halo "standard" star, is shown by a black diamond. From Frebel et al. (2010b).

(Norris et al., 2010c,a; Feltzing et al., 2009). The neutron-capture elements are of extremely low abundances throughout the ultra-faint dwarf galaxies, as well as in Sculptor at low metallicity. The Ba and Sr values observed are well below the abundances found in typical MW halo stars with similar Fe abundances. The low neutron-capture abundances may represent a signature typical of stars with [Fe/H] $\lesssim -2.0$ in dwarf galaxies. Similarly low values have been found in the dSphs Hercules (Koch et al., 2008) and Draco (Fulbright et al., 2004).

Overall, the detailed studies of stars in the ultra-faint dwarfs provide the first evidence that the abundance patterns of light elements ($Z < 30$) in the ultra-faint dwarfs, as well as in Sculptor at [Fe/H] ~ -3.8, are remarkably similar to the Milky Way halo. The agreement renews support that the metal-poor end of the MW halo population could have been built up from destroyed dwarf galaxies. These results above are broadly consistent with the predictions of currently favored cosmological models (Johnston et al. 2008). The majority of the mass presumably in the inner part of the stellar halo (at [Fe/H] ~ -1.2 to -1.6) was formed in much larger systems such as the Magellanic Clouds. New results support a scenario where the ultra-faint dwarf galaxies contributed some individual metal-poor stars that are now found primarily in the outer Galactic halo (although not exclusively). However, these systems may not have been sufficiently numerous to account for the entire metal-poor end of the Fe metallicity distribution of the Milky Way halo. Since the classical dSphs contain more stellar mass and have been shown to also contain at least some of the most metal-poor stars, they could have been a major source of the lowest-metallicity halo content.

5. Outlook

Over the last few years many extremely metal-poor stars have been discovered, particularly in the least-luminous dwarf galaxies. This has opened a new window to study the formation of our Milky Way and also small galaxies in the early Universe via detailed knowledge of the chemical composition of individual stars. Consequently, “near-field cosmology” has received an enormous boost: Through the availability of these new data as well as extensive theoretical simulations on the same topic.

These early successes will be extended and underpinned by future large-scale surveys such as the Australian Skymapper survey (Keller et al., 2007) whose filter combinations have been designed specifically for extracting information on the stellar parameters of each star. This information is vital for characterizing the stellar content of any galaxy, and invaluable for efficiently selecting large numbers of metal-poor stars. No other survey will be able to match these abilities. Skymapper will provide an abundance of metal-poor candidates in need for detailed high-resolution follow up to obtain abundance measurements. By accessing large samples of fainter stars in the outer Galactic halo and dwarf galaxies, the next big frontiers in stellar archaeology and near-field cosmology can be tackled such as the formation history of the halo, and the formation of the first low-mass objects (e.g. Frebel et al. 2007b). Estimates for the lowest observable metallicity in the halo, [Fe/H] $= -7.3$ (Frebel et al., 2009) suggest that stars with such low metallicities can be found, most likely in the outer halo. It thus appears within reach to find the closest relatives to the first stars with the light-collecting power of the next generation of optical telescopes, such as the Giant Magellan Telescope, the thirty Meter Telescope or the European ELT, if equipped with high-resolution spectrographs. Such facilities would enable not only to reach out into the outer halo in search of the most metal-poor stars, but also enable the aquisition of spectra with very high-S/N ratio of somewhat brighter stars. For example, for uranium and lead measurements in r-process enhanced stars exquisite data quality is required, which currently is only possible for the very brightest stars.

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