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# THE DISCOVERY AND ANALYSIS OF VERY METAL-POOR STARS IN THE GALAXY

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■ **Abstract** We discuss the importance of very metal-poor stars to develop an understanding of the nature of the first stars that formed in the Universe and the nucleosynthesis events associated with them, as well as to refine models of galaxy formation, in particular for large spiral galaxies such as the Milky Way. After briefly reviewing the history of the search for very metal-deficient stars in the Galaxy, we summarize ongoing efforts, concentrating on the two large objective-prism surveys that have led to the discovery of the majority of stars with [Fe/H] $< -2.0$ known at present: the HK survey of Beers and collaborators and the Hamburg/ESO survey of Christlieb and collaborators. We then consider the wealth of information that can be gleaned from high-resolution spectroscopic study of very metal-poor stars. We close with a list of open questions and a discussion of new survey techniques that will expand the sample of recognized very metal-deficient stars in the Galaxy by several orders of magnitude.

## 1. INTRODUCTION

One of the fundamental realizations of twentieth-century astronomy was that not all stars in the Galaxy share the same chemical composition. This hard-won knowledge opened the door to numerous modern concepts, cutting across a wide swath of astrophysics. Today it is widely recognized that stars with atmospheric abundances of the heavy elements (such as iron) that are substantially lower than the solar content provide fundamental constraints on numerous issues of contemporary interest. This long and expanding list includes the following:

- *The nature of the Big Bang*: Standard Big Bang cosmologies predict, with increasing precision, the amount of the light element lithium that was present in the Universe after the first minutes of creation. The measured abundance of Li in very metal-poor stars is thought to provide a direct estimate of the single free parameter in these models, the baryon-to-photon ratio.

- *The nature of the first stars*: Contemporary models and observational constraints suggest that star formation began no more than a few hundred million years after the Big Bang and was likely to have been responsible for the production of the first elements heavier than Li. The site of this first element production has been argued to be associated with the explosions of stars of several hundred up to a thousand solar masses (Bromm & Larson 2004). These short-lived objects may have provided the first "seeds" of the heavy elements, thereby strongly influencing the formation of subsequent generations of stars.
- *The first mass function*: The distribution of masses with which stars have formed throughout the history of the Universe is of fundamental importance to the evolution of galaxies. Although the initial mass function (IMF) today may be well described by simple power laws (although not necessarily in all environments, see, e.g., Elmegreen 2005), it is almost certainly different than the first mass function (FMF), which is associated with the earliest star formation in the Universe. Detailed studies of elemental abundance patterns in low-metallicity stars provide one of the few means by which astronomers might peer back and obtain knowledge of the FMF.
- *Predictions of element production by supernovae*: Modern computational advances have led to increasingly sophisticated (yet in many respects still physically primitive) models for the production of light and heavy elements by supernovae explosions. Direct insight into the relevant physics of these models can be obtained from inspection of the abundances of elements in the most metal-deficient stars, which presumably have not suffered pollution from numerous previous generations of stars.
- *The nature of the metallicity distribution function (MDF) of the galactic halo*: Large samples of metal-poor stars are now making it possible to analyze the observed distribution of their metallicities with detailed galactic chemical evolution models. Tests for the presence of structure in the MDF at low metallicity, whether the MDF remains constant as a function of distance throughout the galactic halo, and the important question of whether we are approaching, or have already reached, the limit of low metallicity in the Galaxy can all be addressed with sufficiently large and well-defined samples of very metal-poor stars.
- *The astrophysical site(s) of neutron-capture element production*: Elements beyond the iron peak are formed primarily by captures of neutrons in a variety of astrophysical sites. Models of the s-process, in which the timescales for neutron capture by iron-peak seeds are longer than the time required for beta decay, can be compared with observed abundances recorded by long-lived, low-mass metal-poor stars. Similarly, understanding the nature of the r-process, where the associated neutron captures occur faster than beta decay, is aided by confrontation of model predictions with the abundances of heavy elements observed in very metal-deficient stars.

In this review we discuss these and other applications of analyses based on observations of very metal-poor stars. We do not discuss metal-poor postasymptotic giant branch (post-AGB) stars, because it is believed that their low atmospheric metallicities do not reflect the composition of the gas clouds from which these stars formed (see, e.g., Mathis & Lamers 1992; Waters, Trams & Waelkens 1992; Van Winckel, Waelkens & Waters 1995).

## 1.1. The Nomenclature of Metal-Poor Stars: How Poor Is Poor?

1.1.1. PRELIMINARY DEFINITIONS The abundances of one element with respect to another are often stated by comparison of their ratios with respect to the Sun, using the notation $[\mathrm{A/B}] \equiv \log_{10}(N_\mathrm{A}/N_\mathrm{B})_* - \log_{10}(N_\mathrm{A}/N_\mathrm{B})_\odot$, where $N_\mathrm{A}$ and $N_\mathrm{B}$ refer to the numbers of atoms of elements A and B, respectively. Because of the plethora of absorption lines arising from transitions associated with iron atoms in the Sun, Fe has traditionally been taken as a reference element to enable comparisons of the metallicity of one star with another, quantified as [Fe/H].

It should be kept in mind that, although the Sun provides the standard against which the abundances of elements and their ratios in other stars are measured, the solar quantities themselves have changed as better atomic data and model atmospheres have emerged. For example, the most recent results for CNO, based on consideration of three-dimensional atmosphere models of the Sun and taking into account non-local-thermodynamic-equilibrium (NLTE) corrections, are provided by Asplund, Grevesse & Sauval (2005).

Elemental abundances can also be referred to as an "absolute" scale, relative to the number of hydrogen atoms, defined by $\log\epsilon(\mathrm{A}) \equiv \log_{10}(N_\mathrm{A}/N_\mathrm{H}) + 12.0$, where A can be taken to represent any element. Astronomers often refer to an element as either "under-" or "overabundant" when its logarithmic ratio, compared with the same ratio in the Sun, is lower or higher, hence negative or positive, respectively. For the sake of clarity, unless otherwise stated, the observed elemental abundances in stars are assumed to pertain to their outer atmospheres, where the absorption lines under study are formed, not to a volume average over their interiors.

1.1.2. A PROPOSED STANDARD NOMENCLATURE Over the course of the past half century, as astronomers became aware of the existence of stars of low metallicity in the Galaxy, the nomenclature used to describe differing levels of metal poverty has evolved to the point of confusion. Stars that exhibit [Fe/H] covering the range $-5.4 \leq [\mathrm{Fe/H}] \leq +0.5$ are presently known. At the high end of the scale, above solar, such stars are referred to as metal-rich or super metal-rich stars. On the low end of the scale, the nomenclature is often used inconsistently by different authors. We think it is valuable to standardize, to the extent possible, what is meant by a given level of metal deficiency. In Table 1 we summarize our recommendations.

**TABLE 1** Nomenclature for stars of different metallicity

| [Fe/H] | Term | Acronym |
|---|---|---|
| $> +0.5$ | Super metal-rich | SMR |
| $\sim 0.0$ | Solar | — |
| $< -1.0$ | Metal-poor | MP |
| $< -2.0$ | Very metal-poor | VMP |
| $< -3.0$ | Extremely metal-poor | EMP |
| $< -4.0$ | Ultra metal-poor | UMP |
| $< -5.0$ | Hyper metal-poor | HMP |
| $< -6.0$ | Mega metal-poor | MMP |

Although no stars that fall into the MMP category are presently known, at least one has been recently identified with [Fe/H] $= -5.4$, only a factor of 4 (on a linear scale) different from this value. Hence, looking to the future, it seems useful to include this category.

Note that [Fe/H] does not necessarily refer to the total metal content of a given stellar atmosphere, which might not in fact be significantly less than the solar value, e.g., when the star under consideration also exhibits large overabundances of elements such as C, N, and O. Examples of such stars are discussed in Section 5.

## 1.2. Subclasses of Metal-Poor Stars

Over the past few decades numerous interesting subclasses of metal-poor stars have emerged, some of which can be associated, at least tentatively, with specific astrophysical production sites. It seems appropriate to agree on a standard taxonomy for the major recognized categories. Our suggestions are described below and summarized in Table 2.

We emphasize that it is not yet clear whether many of the divisions we suggest are physically meaningful, in the sense that they result from different nucleosynthetic histories. Furthermore, in some cases there are indications that there exists a continuous, rather than discrete, distribution of the relevant parameters (e.g., enrichment with neutron-capture elements). Hence, a taxonomy based on discrete subclasses of metal-poor stars (as well as the somewhat arbitrary location of the class boundaries in the relevant parameter space) can only be viewed as a first approximation. Although this nomenclature will surely require future revision, we believe that our suggestions are still useful for characterizing the properties of the "zoo" of metal-poor stars.

**TABLE 2** Definition of subclasses of metal-poor stars

| | |
|---|---|
| Neutron-capture-rich stars | |
| r-I | $0.3 \leq$ [Eu/Fe] $\leq +1.0$ and [Ba/Eu] $< 0$ |
| r-II | [Eu/Fe] $> +1.0$ and [Ba/Eu] $< 0$ |
| s | [Ba/Fe] $> +1.0$ and [Ba/Eu] $> +0.5$ |
| r/s | $0.0 <$ [Ba/Eu] $< +0.5$ |
| Carbon-enhanced metal-poor stars | |
| CEMP | [C/Fe] $> +1.0$ |
| CEMP-r | [C/Fe] $> +1.0$ and [Eu/Fe] $> +1.0$ |
| CEMP-s | [C/Fe] $> +1.0$, [Ba/Fe] $> +1.0$, and [Ba/Eu] $> +0.5$ |
| CEMP-r/s | [C/Fe] $> +1.0$ and $0.0 <$ [Ba/Eu] $< +0.5$ |
| CEMP-no | [C/Fe] $> +1.0$ and [Ba/Fe] $< 0$ |

#### 1.2.1. NEUTRON-CAPTURE-ELEMENT RICH, METAL-POOR STARS

The major subclasses of these stars are the r-process-enhanced stars, the s-process-enhanced stars, and a likely third subclass of stars that exhibit enhancements arising from both processes, as we currently understand them. For ease of the following discussion, we divide the r-process enhancement phenomenon in metal-poor stars into two categories: the moderately r-process-enhanced (r-I) stars and the highly r-process-enhanced (r-II) stars. Quantitative definitions can be found in Table 2.

We use Eu as a reference element for the neutron-capture elements that were mainly produced by the r-process in solar-system material, as its abundance is among the most readily measurable in optical spectra of metal-poor stars. We include the condition [Ba/Eu] $< 0$ in our definitions because Eu is produced by the s-process as well. It is thus necessary to distinguish between "pure" r-process-enhanced stars and stars that were highly enriched by material produced in both the r- and s-processes (such as CS 22948-027, CS 29497-034, and HE 2148−1247; see Hill et al., 2000 and Cohen et al. 2003, respectively), which we refer to as r/s-enhanced stars. Adopting the values of Burris et al. (2000) for the solar Ba and Eu abundances and r- and s-fractions of these elements, it follows that a star purely enriched by neutron-capture elements produced in the s-process would have $[\mathrm{Ba/Eu}]_S = +1.5$, whereas $[\mathrm{Ba/Eu}]_r = -0.8$ applies for a pure r-process-enriched star. This information, along with common usage in the recent literature, guides our choices in Table 2.

#### 1.2.2. CARBON-ENHANCED METAL-POOR STARS

As discussed below, one of the surprising results of contemporary objective-prism surveys was the recognition that many VMP stars exhibit enhancements of their carbon-to-iron ratios that are up to several orders of magnitude larger than the solar ratio. For convenience, this broad category of objects is defined to include stars with [C/Fe] $> +1.0$; such stars are referred to as carbon-enhanced metal-poor (CEMP) stars. (Note that some authors prefer a division at [C/Fe] $> +0.5$; the nomenclature is not standard at present.)

Within the CEMP classification, there are at least several subclasses that have been recognized. These include stars that also exhibit r-process-enhancement, such as CS 22892-052 (Sneden et al. 2003), which we refer to as CEMP-r stars. Note that the subclasses of CEMP stars are not mutually exclusive with respect to the neutron-capture subclasses defined above, e.g., CS 22892-052 is also an r-II star. CEMP stars that satisfy the definition of s-process enhancement are referred to as CEMP-s stars, whereas those that exhibit both r- and s-process enhancement are CEMP-r/s stars. Recent studies (e.g., Aoki et al. 2002a) have also indicated the presence of CEMP stars that enhibit no strong overabundances of neutron-capture elements; these are referred to as CEMP-no stars.

### 1.3. Overview of This Review

In Section 2 we briefly consider the history of the search for VMP stars, beginning with the first hints of their existence and early confirmations of their presence in the Galaxy. In Section 3 we examine the primary techniques that have been developed thus far to greatly expand the database of known VMP stars. In Section 4 we describe several detailed studies of VMP stars and consider their impact on modern astrophysics. The properties of the lowest metallicity stars currently known are reviewed in Section 5. We conclude in Section 6 with a discussion of the issues that remain to be explored with the existing database of VMP stars and describe future survey efforts, concentrating on the questions of greatest interest which they might be used to address.

## 2. HISTORY

### 2.1. First Suspicions

The first direct clues to the existence of metal-poor stars arose from discrepancies that were noted between classifications of stellar spectra based on the strength of the Balmer lines of hydrogen (e.g., the Henry Draper Catalog) and classifications based on characteristics other than the Balmer lines, in particular the strengths of metallic lines. Within a span of 2 years, investigations of these peculiar stars led to two major breakthroughs: (*a*) the first detailed spectroscopic analyses of HD 19445 and HD 140283 by Chamberlain & Aller (1951), who demonstrated that the peculiarities could be understood by adopting a deficiency of a factor of 10 (or more) of the metal content in these stars relative to the solar metallicity and (*b*) the association between the "weak-lined stars" and high space velocities made by Schwarzschild & Schwarzschild (1950) and (in the same issue of the *Astrophysical Journal*) by Roman (1950).

It is interesting to note that, although Schwarzschild & Schwarzschild were unable to demonstrate significant metal deficiencies in their sample stars relative to the Sun, they did report that the strength of the CH G-band was significantly higher among their high-velocity stars as compared with their lower-velocity objects. This may have been the first tentative evidence for the carbon-enhancement phenomenon in metal-poor stars, discussed in more detail in Section 4.3.

Roman's work, in particular, greatly influenced early ideas for the formation and evolution of the Milky Way. Eventually, her ideas were incorporated in the pioneering work of Eggen, Lynden-Bell & Sandage (1962, hereafter ELS). The ELS assertion of the existence of a strong correlation between the metallicity (as inferred from the ultraviolet excess; see Section 3.2) of stars and the eccentricities of their orbits in the Galaxy inspired several decades of subsequent investigations. Although there is a clear separation in metallicity between stars with primarily disk-like (low eccentricity) orbits and those with primarily halo-like (high-eccentricity) orbits, the correlation largely breaks down for stars chosen on the basis of their low metallicity in a kinematically unbiased fashion (e.g., Yoshii & Saio 1979; Beers et al. 2000; Chiba & Beers 2000, in particular their figure 6).

## 2.2. Confirmation of the Existence of VMP Stars

The desire to test the reality of the ELS claim led Bond (1970) and, later, Bidelman & MacConnell (1973) to search specifically for stars of low metallicity on the basis of spectroscopy alone, rather than relying on a potentially biased selection based on high proper motions. These and other data, in particular the kinematics and abundances of galactic globular clusters, led Searle & Zinn (1978) to propose that the Galaxy formed from the accretion of small, independent subgalactic units, now cast by modern workers into the framework of the Cold Dark Matter hierarchical assembly model (e.g., Primack 2002).

Further investigations by Bond (1980) resulted in the discovery of a substantially expanded list of metal-poor stars. Interestingly, Bond's own analysis led him to question whether there existed an effective lower limit to the metallicity of halo stars at around [Fe/H] $= -2.5$, i.e., near the inferred abundances of the lowest-metallicity halo globular clusters (see Bond 1981). The question was of significant importance, as it directly focused attention on whether or not long-lived, low-mass stars at very low metallicity were formed in the early Universe. Indeed, at the time, general wisdom held that the lack of cooling channels made available by heavy elements would have precluded the possibility of early low-mass star formation. Even at that time there were papers that disagreed with this assertion (e.g., Yoshii & Sabano 1979, Yoshii & Saio 1986). Nature has demonstrated that such stars did indeed form, presumably relying primarily on cooling from molecular H pathways (e.g., Palla, Salpeter & Stahler 1983), or on cooling channels opened by the presence of dust (Schneider et al. 2003), or carbon and/or oxygen (Umeda & Nomoto 2003, Bromm & Loeb 2003) in the early Universe.

## 2.3. Breaking the Globular Cluster "Barrier"

Despite arguments that the halo of the Galaxy did not include substantial numbers of stars with [Fe/H] $< -3.0$, by the mid-1980s at least two counter-examples were known. These were the subdwarf G 64-12 (a star originally noted for its extremely high space velocity, over 400 km $s^{-1}$), for which Carney & Peterson (1981) reported [Fe/H] = −3.5, and the giant CD −38° 245 (a star noted to exhibit a nearly continuous spectrum on the objective-prism plates of Slettebak & Brundage 1971), which Bessell & Norris (1984) reported to have [Fe/H] = −4.5. Modern values for the metallicities of these two stars are [Fe/H] = −3.2 (Ryan, Norris & Beers 1999) and [Fe/H] = −4.0 (Norris, Beers & Ryan 2000; François et al. 2003), respectively.

Prior to the late 1970s, objective-prism surveys for metal-deficient stars were primarily conducted at resolutions that precluded classifications of objects fainter than about $B \simeq 12$–13, and hence were restricted to the inspection of halo dwarfs whose orbits brought them close to the solar neighborhood, or brighter giants that were only a few kpc distant. In the late 1970s, Preston and Shectman initiated a survey that attempted to push farther out into the halo, where effective in situ searches could be conducted, using a modified prism-survey technique. The crucial alteration was the insertion of an interference filter in front of the photographic plates that only passed roughly 150 Å of spectrum around the region of the Ca II K line at 3933 Å, the strongest metallic line in the optical spectra of most stars. Its absence, or clear weakness, based on visual inspection of the plates, was taken to indicate that the overall level of metals in candidate metal-poor stars was quite low. The interference filter served to reduce the effects of sky fog and also prevented spectral overlap in the (widened) spectra, thereby allowing the prism technique to extend to much fainter apparent magnitudes, around $B \simeq 15.5$–16. At these fainter limits, one could identify giants out to some 10 kpc from the Sun, well into the halo of the Galaxy, and outside the regions associated with the disk population(s).

Beers, Preston & Shectman (1985) summarized the first results of the so-called Preston/Shectman Survey (now referred to as the HK Survey) and claimed (based on 1–2 Å spectroscopic follow-up of the early candidates from this survey) that the Galaxy did indeed exhibit a significant population of stars with [Fe/H] ≤ −3.0, including five objects they asserted had lower metallicities than G 64-12. Subsequent high-resolution spectroscopic analysis of one of these stars (CS 22876-032) by Molaro & Castelli (1990) confirmed a metallicity on the order of [Fe/H] = −4.0. More recent values for this star place the metallicity somewhat higher, [Fe/H] = −3.7, between the abundances of G 64-12 and CD −38° 245. The modern searches for the most metal-poor stars in the Galaxy were underway.

## 3. TECHNIQUES

Owing to their rarity, the road to obtaining elemental abundances for metal-poor stars in the Galaxy is long and arduous. The process usually involves three major observational steps (see Figure 1): (*a*) A wide-angle survey must be carried out, and candidate metal-poor stars must be selected; (*b*) moderate-resolution spectroscopic follow-up observations of the candidates are then required to validate the genuine metal-poor stars among them; finally, (*c*) high-resolution spectroscopy of the most interesting candidates emerging from step 2 must be obtained. Step 1 can be carried out in many different ways, for example, with proper-motion surveys (Section 3.1) or colorimetric surveys (Section 3.2). However, spectroscopic surveys (Section 3.3) provide the most efficient means (in terms of the fraction of genuine metal-poor stars identified among the selected candidates) to discover large numbers of VMP stars. This approach has the additional advantage that the samples obtained are kinematically unbiased, which is clearly not the case for proper-motion selected samples.

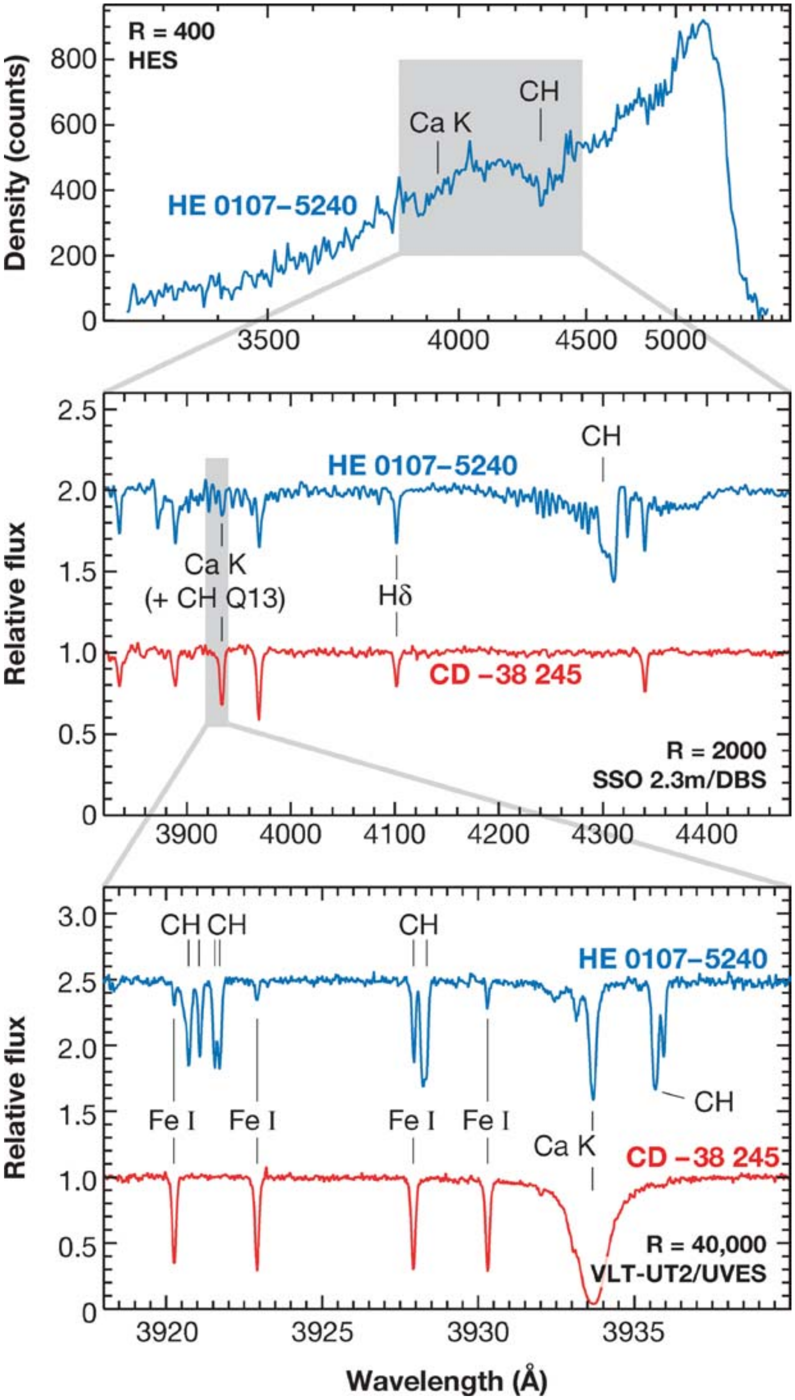
In the recent work of Christlieb et al. (2004), an additional observational step has been introduced to this procedure, "snapshot" high-resolution spectroscopy. This step was triggered by interest in the identification of specific (rare) subclasses of metal-poor stars for detailed studies, e.g., r-I, r-II, and other neutron-capture-rich metal-poor stars. The snapshot spectroscopy technique is described in Section 3.4.

## 3.1. Proper-Motion-Based Searches

Proper-motion measurements of stars in the Galaxy have been carried out for a very long time. Indeed, precision measurement of stellar positions was one of the classic occupations of late-nineteenth and early-twentieth-century astronomers. This is important because measurement of the generally quite small tangential motions of stars on the sky requires two (or more) accurate positions, separated in time by as long a baseline as is feasible, in order to minimize error.

Once the connection was made between the velocities of stars and their abundances, astronomers began to systematically study objects that exhibited the largest measured proper motions. Originally, this was done with broadband photometry (e.g., UBV), making use of the fact that the depletion of metals in a stellar atmosphere has a detectable effect on the emergent flux, in particular in the blue region where the density of metallicity absorption lines is highest. Photometric estimates of metallicity for stars with available proper-motion measurements formed the basis for the classic study of ELS.

More recently, several large spectroscopic follow-up campaigns have been carried out to search for low-metallicity stars based on proper-motion selected samples, culminating in the papers of Ryan & Norris (1991) and Carney et al. (1994). Although a number of interesting low-metallicity stars have indeed resulted from these efforts, the yield of VMP stars is rather low; in the published work, fewer than 10% of the stars in these catalogs have [Fe/H] $< -2.0$. This is a direct result of the fact that the metallicity distribution function (MDF) of halo stars peaks around [Fe/H] $= -1.6$ and falls rapidly with declining metal abundance. Hence, the great majority of candidates selected on the basis of their large proper motions alone are expected to have [Fe/H] $> -2.0$. Nevertheless, this procedure may become of increasing value in the near future, as the advent of modern large-scale astrometric measurements expands the total input samples for searches of this sort by many orders of magnitude. Among the recent large efforts to be noted are the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HES
Density (counts)
800
600
400
200
0
Ca K
CH
HE 0107−5240
3500
4000
4500
5000
2.5
2.0
1.5
1.0
0.5
0
CH
HE 0107−5240
Ca K
(+ CH Q13)
Hδ
Relative flux
CD −38 245
R = 2000
SSO 2.3m/DBS
3900
4000
4100
4200
4300
4400
3.0
2.5
2.0
1.5
1.0
0.5
0
CH CH
CH
HE 0107−5240
Fe I
Fe I
Fe I
Fe I
Ca K
CH
CD −38 245
R = 40,000
VLT-UT2/UVES
Relative flux
3920
3925
3930
3935
Wavelength (Å)

STARNET catalog (Röser 1996), the SuperCOSMOS catalog (Hambly et al. 2001), the Northern Proper Motion Survey (Hanson et al. 2004), the Southern Proper Motion Survey (Girard et al. 2004), and the U.S. Naval Observatory CCD Astrograph Catalog (Zacharias et al. 2004). The most ambitious ground-based effort to date is that of the Sloan Digital Sky Survey (SDSS; York et al. 2000), where precision modern-epoch astrometry is being obtained for all detected (and nonsaturated, i.e., $14.0 \leq g \leq 20.0$) stars in the SDSS footprint, which are then compared with machine scans of previous-generation photographic plates taken between the 1950s and the 1990s (Munn et al. 2004).

## 3.2. Colorimetric Searches

The blanketing effect that metallic lines have on the emergent flux from a star can be exploited to search for stars of low metallicity. Sandage (1969) refined and quantified this effect with the introduction of the $\delta(U - B)_{0.6}$ index, which compared the $U - B$ colors of stars with that observed for solar-metallicity stars, normalized to a consistent color of $B - V = 0.6$. For stars with $0.35 \leq B - V \leq 0.8$, the $\delta(U - B)_{0.6}$ technique provides metallicity estimates with a scatter on the order of $\sim$0.5 dex over the metallicity range $-2.0 \leq$ [Fe/H] $\leq 0.0$ (see figure 3 of Norris & Ryan 1989). Although the blanketing effect (as measured with broad-band filters) nearly vanishes below [Fe/H] $= -2.0$, one may still make use of the technique to separate stars that are likely to be above or below [Fe/H] $= -2.0$, at least within the color range where it applies.

Alternative photometric systems provide the possibility of improved sensitivity to metallicity. For example, Geisler (1984) describes how a combination of broad-band filters from the Washington system ($T_2$, $M$; Canterna 1976) and an intermediate-band filter from the DDO system ($DDO51$; McClure 1976) can be used to simultaneously obtain photometric estimates (or limits) on the surface gravities and metallicities of dwarfs and giants over a reasonable range of temperatures. Geisler et al. (1991) demonstrated that a combination of the Washington filters $C$, $M$, $T_2$ is particularly well-suited for metallity estimation of G- and K-type giants. These techniques, or variations on them, have been employed by Majewski

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**Figure 1** The three major observational steps toward obtaining elemental abundances of metal-poor stars: (*a*) Wide-angle surveys (e.g., objective-prism surveys) yield candidate metal-poor stars; (*b*) vetting of the candidates by moderate-resolution follow-up spectroscopy; and (*c*) high-resolution spectroscopy of confirmed metal-poor candidates. The star shown in this example, HE 0107−5240, is one of the most iron-poor stars yet discovered. The strengths of its absorption lines are compared with the formerly most iron-poor giant known, CD −38° 245. The spectra shown in the *lower two panels* have been divided by the continuum. The resolving power, $R = \lambda/\Delta\lambda$, of the spectra is indicated along the right-hand side of each panel. Prominent atomic and molecular species are labeled.

et al. (2000) and Morrison et al. (2000) in large-scale studies of the structure of the halo of the Milky Way. Du et al. (2004) describe the use of a system of 15 intermediate-band filters (the BATC system), covering the wavelength range $3000 \leq \lambda \leq 10{,}000$ Å, to obtain approximate metallicity estimates for samples of dwarfs within 5 kpc of the galactic plane. A similar multiband approach is planned with the ESA Gaia satellite (see Section 6.4.5).

The intermediate-band Strömgren ($uvby$) system provides superior metallicity (as well as gravity and temperature) sensitivity, at least down to abundances on the order of [Fe/H] $= -2.5$ to $-3.0$. Schuster and collaborators have used this approach in a series of papers to estimate metallicities of thick-disk and halo stars, concentrating on dwarfs originally chosen on the basis of their proper motions (see, e.g., Schuster, Parrao & Contreras Martinez 1993). Schuster et al. (2004) have reported metallicity estimates for some 500 stars selected from the HK Survey of Beers, Preston & Shectman (1985, 1992). As demonstrated in that paper, the metallicities obtained by the Strömgren $m_1$ index compare quite well with those obtained from medium-resolution spectroscopy, except for the EMP stars ([Fe/H] $\leq -3.0$) and those that exhibit peculiarities (such as enhanced carbon) that confound the photometric abundance estimates. Anthony-Twarog & Twarog (1998) and Anthony-Twarog et al. (2000) have carried out similar measurements for dwarfs, subgiants, and giants, making use of an additional narrow filter centered on the Ca II K line, to extend the metallicity sensitivity down to at least [Fe/H] $= -3.5$.

The SDSS has already generated the largest homogeneous catalog of well-calibrated photometry for Galactic stars, using the broad-band *ugriz* system (see, e.g., Ivezić et al. 2004). By the end of the primary SDSS imaging survey in July 2005, such data will exist for over 100 million stars. The SEGUE project, part of an extension to the original SDSS (see Section 6.4.3), will enlarge this number by more than a factor of 2. The utility of the SDSS photometric system for the identification of low-metallicity stars has been explored already by Lenz et al. (1998) and more recently by Helmi et al. (2003). Because of the use of broad-band filters, the SDSS system is less than ideal for this application. However, large numbers of candidates can be potentially generated; hence, if highly multiplexed spectrographs are employed for obtaining follow-up verification, the efficiency of candidate selection is not a crucial limitation.

## 3.3. Objective-Prism Searches

Wide-angle, low-resolution, spectroscopic surveys presently provide the most efficient means with which to identify metal-poor stars. Until a few years ago, Schmidt telescopes with objective prisms and photographic plates have been employed, yielding slitless spectroscopy of millions of objects. Recently, some Schmidt telescopes have been equipped with multifiber spectrographs (e.g., the 1.20 m UK Schmidt/6dF) or CCD cameras (e.g., the 1.05 m Kiso Schmidt) and are being used for extensive survey work (see Section 6.4). Below we discuss the two most important objective-prism surveys that have been used for the identification of metal-poor stars in the Galaxy.

3.3.1. THE HK SURVEY The primary source of VMP stars, until quite recently, was the HK survey of Beers and colleagues (Beers, Preston & Shectman 1985, 1992; Beers 1999). Survey areas of 2800 deg$^2$ and 4100 deg$^2$ were covered with objective-prism plates in the Northern and Southern Hemisphere, respectively, using the 0.6 m Burrell and Curtis Schmidt telescopes. Thus far, the HK survey has yielded approximately 1000 stars with $[Fe/H] < -2.0$ and on the order of 100 stars with $[Fe/H] < -3.0$.

Selection of potentially metal-poor stars in the HK survey was accomplished by visual inspection of the widened objective-prism spectra with a binocular 10× microscope. Candidates were identified on the basis of the observed strengths of their Ca II K lines and grouped into rough categories based on this criterion (e.g., possibly metal-poor, metal-poor, and extremely metal-poor). In this process, a total of approximately 10,000 metal-poor candidates was selected, roughly half of which have had medium-resolution follow-up spectroscopy obtained to date (primarily the candidates in the Southern Hemisphere).

The visual inspection process was performed without knowledge of the stellar colors (hence temperatures); thus, it was expected that the HK-survey candidates would carry a rather severe temperature-related bias. That is, cooler metal-deficient stars would likely be missed because of the enhanced strengths of their Ca II K lines at lower temperatures. In addition, stars of higher temperature with intermediate abundances would be included in larger numbers than might be desired because of the apparent weakness of their Ca II K lines. These biases become less of a problem at the lowest metallicities, below $[Fe/H] = -2.0$, where the Ca II lines of even quite cool stars are difficult to detect at the spectral resolution of the HK survey ($\sim$5 Å).

Efforts are under way to recover numerous VMP HK-survey giants, by means of artificial neural network (ANN) classifications of spectra extracted from digitized HK survey plates (Rhee 2000), in combination with *JHK* colors from the 2MASS survey (Skrutskie et al. 1997). This effort, known as the HK-II survey, should lift many of the selection biases that were known to exist in the visually selected HK-I survey. Scans of the narrow spectral region available on these plates are used to estimate pseudo-equivalent widths of the Ca II H and K lines, as well as to quantify the slope of the stellar continuum. This information, along with the externally available *JHK* photometry, is input to specially designed ANNs that estimate a metallicity and broad-band $B - V$ color for each star. Rhee and collaborators (in preparation) have found that numerous metal-poor candidates that were not identified in the HK-I survey, especially among the cooler stars, exhibit $[Fe/H] < -2.0$, based on medium-resolution spectroscopic follow-up. To date, some 1000 follow-up spectra of HK-II candidates have been obtained; it is expected that several thousand additional candidates will be observed over the course of the next few years.

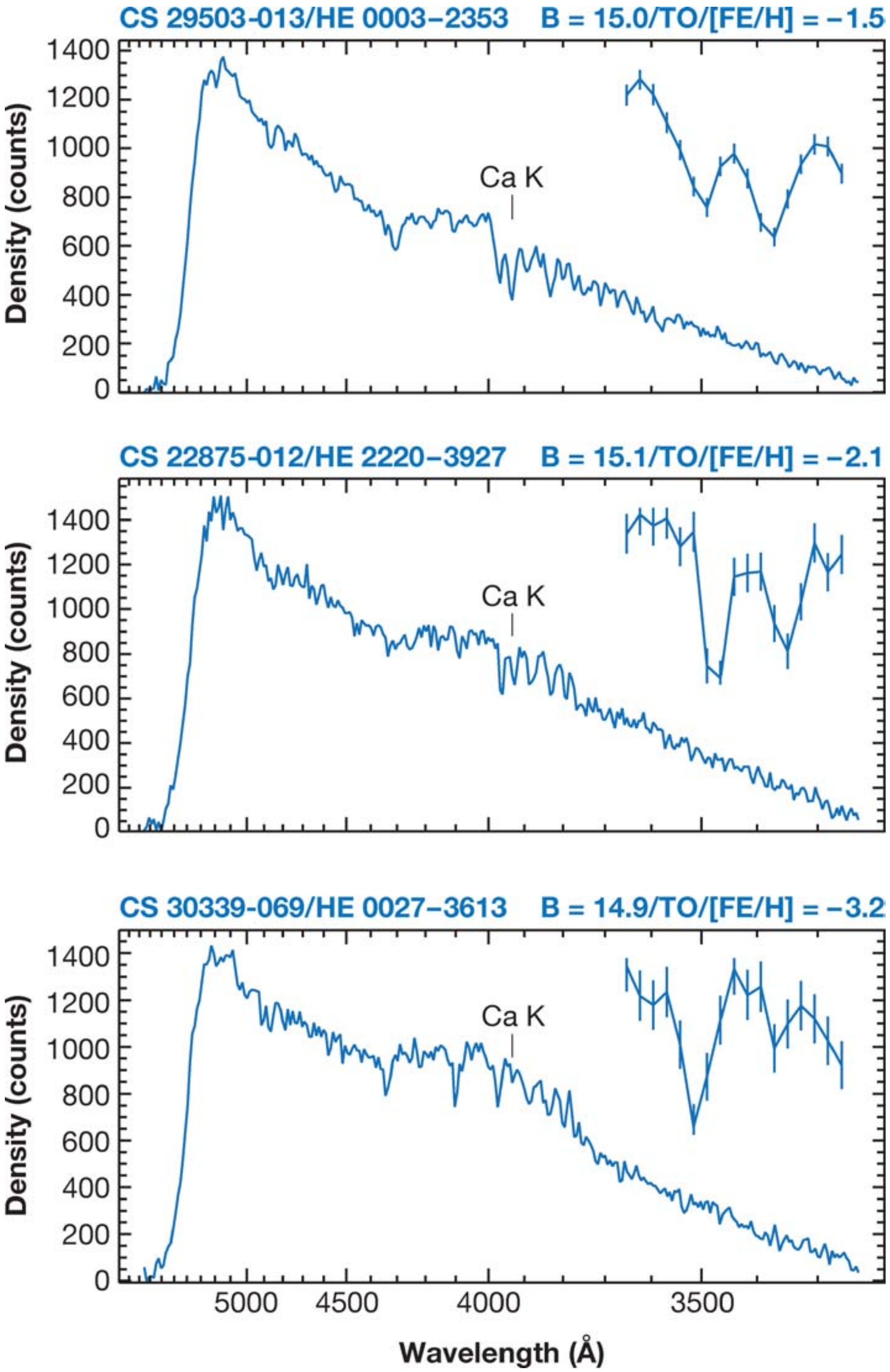
3.3.2. THE HAMBURG/ESO SURVEY The Hamburg/ESO objective-prism survey (HES; Wisotzki et al. 2000) offers the opportunity to increase the number of EMP stars by almost an order of magnitude with respect to the HK survey, because the HES reaches apparent magnitudes that are approximately two magnitudes deeper, i.e., $10.0 \lesssim B \lesssim 17.5$, as compared with $11.0 \lesssim B \lesssim 15.5$ in the HK survey. The HES also covers regions of the sky that were not included in the HK survey; the total southern ($\delta < +2.5^\circ$) extragalactic ($|b| \gtrsim 30^\circ$) sky is included in the footprint of the HES. The HES objective-prism plates were obtained with the ESO 1 m-Schmidt telescope and then were scanned and reduced at the Hamburger Sternwarte.

Candidate metal-poor stars are selected in the HES database of digital objective-prism spectra, using quantitative criteria, including automatic spectral classification (Christlieb, Wisotzki & Graßhoff 2002). The strength of the Ca II K line is determined using the `KP` (Beers et al. 1999) line index, as measured directly from the objective-prism spectra. Because of the broad wavelength range covered by the HES spectra, it is also possible to determine $B - V$ directly from the prism spectra, with an accuracy of ~0.1 mag (Christlieb et al. 2001). Stars that have Ca II K lines weaker than expected for their estimated $B - V$ colors and an approximate metallicity of $[\mathrm{Fe/H}] = -2.5$ are selected as low-metallicity candidates. Figure 2 provides an illustration of the effect of decreasing metallicity on HES spectra.

In total, approximately 10,000 candidate metal-poor stars in the magnitude range $10 \lesssim B \lesssim 17.5$ have been selected in 329 (out of 380) HES fields, covering a nominal area of 8225 square degrees of the southern sky. Follow-up medium-resolution observations of ~4000 candidates have been obtained so far, and more than 200 EMP stars with $[\mathrm{Fe/H}] < -3.0$ have been identified.

Table 3 compares the "effective yields" (as defined by Beers 2000) of metal-poor stars in the HK survey and in the HES—that is, the fraction of genuine metal-poor stars below a given [Fe/H] in the observed candidate sample. In the table, $N$ refers to the total number of stars from which the statistic has been derived. From inspection of the table, it appears that the HES is roughly twice as efficient as the HK survey in finding EMP stars with $[\mathrm{Fe/H}] < -3.0$, even when $B - V$ photometry is used in the latter survey to aid preselection, and six times as efficient compared with the HK survey without the use of $B - V$ photometry. The higher yields of the HES can mainly be attributed to the fact that approximate $B - V$ colors are available in the HES and are used as part of the selection process, as well

**Figure 2** HES spectra of known metal-poor stars identified in the HK survey. The stars shown have similar temperatures. Metallicities of these stars, obtained from medium-resolution spectroscopy, are indicated on the *upper right* of each panel. Note that wavelength is decreasing from left to right. The sharp cutoff at ~5400 Å is due to the sensitivity cutoff of the IIIa-J photographic emulsion used in the HES. The *inset* in each panel is an enlargement of the spectrum in the region of the Ca II H + H$\epsilon$ and Ca II K lines. Note the clear decrease of the strength of the Ca II K line with declining metallicity.



CS 29503-013/HE 0003−2353 B = 15.0/TO/[FE/H] = −1.5

CS 22875-012/HE 2220−3927 B = 15.1/TO/[FE/H] = −2.1

CS 30339-069/HE 0027−3613 B = 14.9/TO/[FE/H] = −3.2

**TABLE 3** "Effective yields" of metal-poor stars

| | | [Fe/H] | | |
|---|---|---|---|---|
| **Survey** | *N* | **<−2.0** | **<−2.5** | **<−3.0** |
| HK survey/no $B - V$ | 2614 | 11% | 4% | 1% |
| HK survey/with $B - V$ | 2140 | 32% | 11% | 3% |
| HES (faint turnoff stars) | 571 | 59% | 21% | 6% |
| HES (faint giants) | 643 | 50% | 20% | 6% |

as the higher and more-uniform quality of the HES spectra and the employment of quantitative selection criteria.

At the bright end of the survey, i.e., in the range $10 < B < 14$, the HES spectra suffer from saturation effects (in particular in the red), which makes the metal-poor candidate selection a challenge. Recent follow-up observations have shown, however, that the selection efficiency of VMP stars amongst the brighter HES candidates is comparable to, or perhaps even better than, the efficiency of the HK survey when no additional color information is employed (A. Frebel, N. Christlieb, J.E. Norris, T.C. Beers, M.S. Bessell, et al., in preparation).

The HES is a very rich source for VMP giants; about 60% of the candidates are in the color range $0.5 < B - V < 1.2$. The present HK-survey sample, by contrast, is dominated by hotter stars near the main-sequence turnoff, due to the temperature-related bias described above. As a result, only roughly 20% of the HK-survey stars are VMP giants. Interested readers may wish to inspect the "as-observed" metallicity distribution functions of these two surveys presented in Christlieb (2003).

## 3.4. Snapshot Spectroscopy

To improve our knowledge of the early phases of the chemical history of the Galaxy, and the nucleosynthesis processes that operated in the early Universe, samples of metal-poor stars need to be larger, better-defined, and more uniformly analyzed than is the case at present. For example, detailed information on the s- and r-processes is provided by metal-poor stars that exhibit large overabundances of elements associated with these nucleosynthesis pathways. Concerning the r-process, only 4–5% of the giants with [Fe/H] $< -2.5$ are r-II stars, i.e., this is a rare subclass of stars amongst stars that are rare themselves. It is clearly important to have samples of sufficient size to allow for accurate estimation of the frequency of rare phenomena. Furthermore, recent studies (see Section 4.7) have focused attention on the importance of obtaining precise measures of the element-to-element scatter in large samples of metal-poor stars, in addition to quantifying their overall trends. Finally, it would be desirable to develop samples of metal-poor stars that can serve as unbiased "test beds" for comparison with predicted abundance yields from supernovae, AGB stars, or other proposed sites of element production, folded together with models of chemical evolution and mixing in the early Galaxy.

As an example of where we believe the field is quickly heading, Christlieb et al. (2004) describe the Hamburg/ESO R-process-Enhanced Star (HERES) survey, which has successfully employed "snapshot" spectra (i.e., moderately high-resolution spectra with resolving powers of $R = \lambda/\Delta\lambda = 20000$ and modest signal-to-noise ratios of $S/N \sim 30/1$ to $50/1$; see Figure 3) to identify r-II and other interesting stars amongst candidate HES giants with [Fe/H] $< -2.5$. A uniform analysis of the several hundred snapshot spectra obtained thus far is made practical by the use of automated abundance techniques (Barklem et al., 2005); this approach obtains measurements for roughly 15–20 elemental species per star. The resulting database of abundance information is the most extensive probe of early galactic nucleosynthesis obtained to date.

Snapshot spectra have also been obtained by Lai et al. (2004), using Keck/ESI, for 110 HK-survey candidate metal-poor stars collected from the literature. These authors employed a lower spectral resolution than in the HERES project (i.e., $R \sim 7000$); as a result, abundances could only be determined for six elements (Fe, Mg, Ca, Ti, Cr, and Ba).

Finally, the history of the discoveries of the most iron-poor stars known at present (HE 0107−5240 and HE 1327−2326) (see Section 5.2) reminds us that the metallicities of stars with [Fe/H] $< -5.0$ can be overestimated (when based solely on medium-resolution spectroscopy), by as much as factor of 30, due to contamination of the Ca II K line by molecular carbon lines or by interstellar Ca II K, or if there exist large overabundances of the $\alpha$-element Ca. As a result, snapshot spectra are needed to reliably determine the [Fe/H] of EMP stars with [Fe/H] $\lesssim -3.5$ and to identify the HMP stars with [Fe/H] $< -5.0$ among them.

## 4. THE IMPACT OF VMP STARS ON ASTROPHYSICS

The large samples of VMP stars that have emerged in the past decade have led to prodigious research activity, as many groups of astronomers exploit the information they provide on the nature and evolution of element production in the early Galaxy and in the Universe. In this section we consider some of the most interesting and important recent results. We begin with a discussion of limitations imposed by the uncertainties in analysis procedures that are in common use at present, then describe efforts to obtain isotopic abundances, for a limited set of elements, from the spectra of metal-poor stars. This is followed by a summary of the astrophysical interpretation of various classes of VMP stars based on recent measurements. We then consider two important sets of recent analyses, for the light element lithium and for the general behavior of heavy elements in low-metallicity stars.

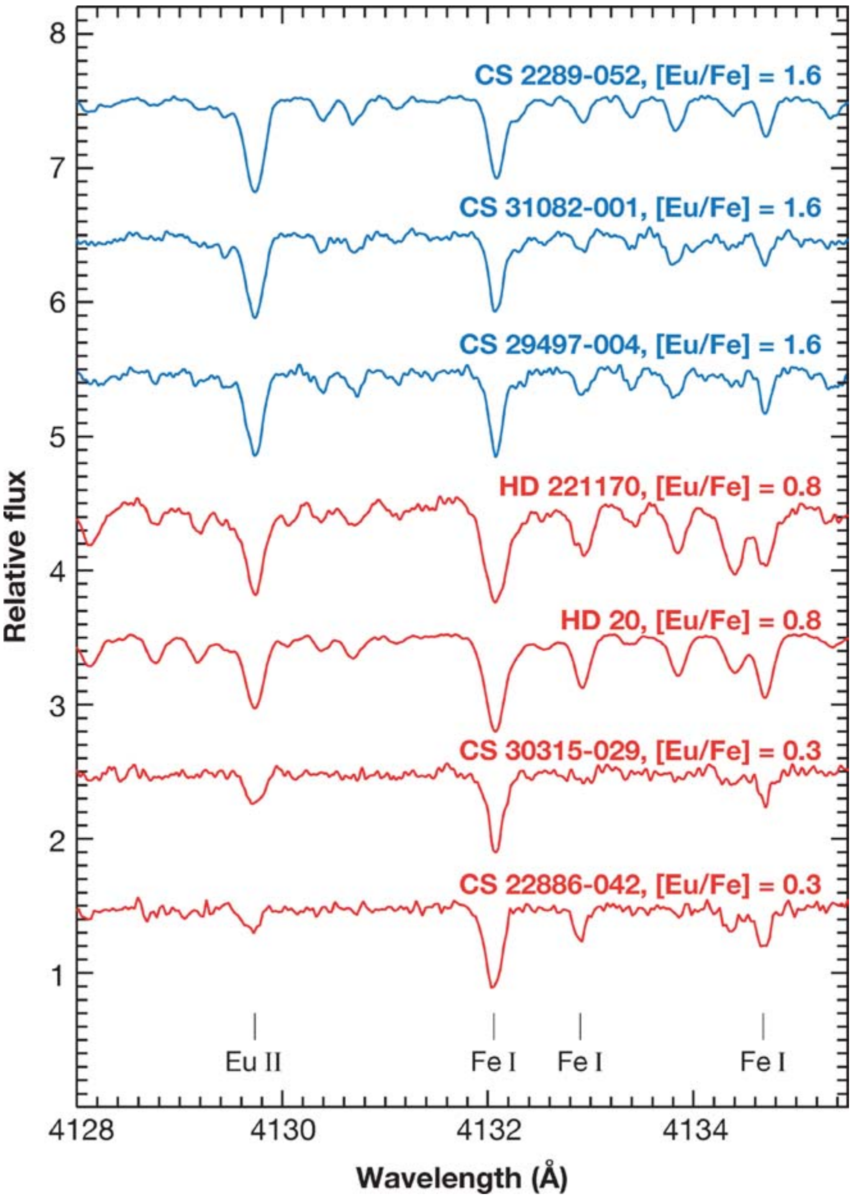


**Figure 3** The spectral region around the Eu II 4129.73 Å line in several known r-II (CS 22892-052, CS 31082-001) and r-I (HD 222170, HD 20) stars observed during the HERES snapshot survey, as well as 1 (of 8) newly identified r-II stars (CS 29497-004), and 2 (of 35) newly identified r-I stars (CS 30315-029, CS 22886-042) discovered during HERES survey. The level of r-process enhancement, as indicated by [Eu/Fe], is shown above each spectrum.

## 4.1. Limitations of Present Analysis Techniques

Elemental abundance estimates are still mostly derived from high-resolution spectra using one-dimensional model atmospheres and carrying out line-formation calculations in LTE. However, as reviewed by Asplund (2005, this volume), considerable systematic errors may arise if this "classical" abundance analysis method is employed. The systematic errors are perhaps most pronounced in metal-poor stars and may be as high as 1 dex at the lowest metallicities and for some molecular species. The reason is that 3D hydrodynamical simulations, which appear to be a much more realistic representation of actual stellar atmospheres, yield much cooler temperatures in the outer layers of the stars. Minority species (such as Mg I, Ca I, Al I, or Fe I) and low-excitation lines can be affected in the same way; i.e., the abundances can be overestimated in 1D LTE analyses. On the other hand, NLTE effects may lead to systematic underestimation of abundances, so that the effects might at least partly cancel. In the case of Li I, they cancel almost fully, i.e., to within less than 0.1 dex (Asplund, Carlsson & Botnen 2003), but one cannot safely assume that this is the case for species of other elements as well.

Additional systematic abundance errors, on the order of a few tenths of a dex, may arise from errors in stellar parameters (in particular effective temperature) and slightly smaller errors due to uncertainties in atomic data (see the recent review of Gustafsson 2004). Therefore, one has to be very careful when compiling abundances from the literature for studies of abundance trends, and in particular for the estimation of scatter around these trends, because systematic offsets between abundances derived by different authors may lead to false abundance trends and/or overestimation of the true "cosmic" abundance scatter of a given element.

## 4.2. Isotopic Abundances

Nucleosynthesis calculations, e.g., the yields of Type II SNe, and models for the production of nuclei in AGB stars, predict the isotopic compositions of the species that are formed; the stable, long-lived isotopes are then summed to predict the resulting elemental abundances. Detailed measurements of individual isotopes are now routinely obtained from the analysis of solar-system material, such as in meteorites (see, e.g., Clayton & Nittler 2004). In stars, however, the vast majority of isotopes remain beyond the realm of direct spectroscopic measurement because the tiny isotopic shifts are generally smaller than the width of the intrinsic line profiles.

There are, however, a number of important exceptions. In Section 4.6 we summarize the important recent measurements of $^{6}$Li. Below we consider a few other examples.

Molecular features, such as the CH and CN bands, provide the opportunity to measure the abundance of $^{13}$C, usually expressed relative to $^{12}$C as $^{12}$C/$^{13}$C. The carbon isotopic ratio has been used for decades to infer the degree of mixing of internally processed material with the outer layers of stellar atmospheres (see, e.g., Spite et al. 2004). Similarly, the MgH bands near 5140 Å have been exploited to infer the ratios of $^{24}$Mg, $^{25}$Mg, and $^{26}$Mg, both for MP and VMP stars in the halo (Yong, Lambert & Ivans 2003) and in globular-cluster giants (Yong et al. 2003). The Mg isotope measurements are of particular value, because they provide probes of the likely nucleosynthetic history of the star, i.e., whether its isotopic pattern arises from pre-supernova evolution of massive stars, or whether additional processes, such as the contribution from intermediate-mass AGB stars, are required.

Neutron-capture processes can also be effectively probed, for a small number of elements, with isotopic measurements in stars. In the element barium, for instance, analysis of solar-system isotopes indicates rather different contributions from the s- and r-processes to the mixture of its odd and even isotopes. Arlandini et al. (1999) report $f^{s}_{\rm odd} = 0.11$, versus $f^{r}_{\rm odd} = 0.46$, where $f_{\rm odd} = [{\rm N}(^{135}{\rm Ba}) + {\rm N}(^{137}{\rm Ba})]/{\rm N(Ba)}$. Lambert & Allende Prieto (2002) have presented a detailed study of the isotopic mixture of barium in the VMP subgiant HD 140283. Their measurements challenged an earlier study of the isotopic mixture by Magain (1995), who claimed that the observations were inconsistent with a pure r-process origin of barium. The Lambert & Allende Prieto analysis of the profile of the Ba II 4554 Å line indicated that a solar-like r-process mixture of odd and even isotopes of Ba could indeed provide a reasonable fit to the observations.

Sneden et al. (2002) have reported measurements of the fraction of Eu isotopes in the r-process-enhanced stars CS 22892-052, HD 115444, and BD +17° 3248. Similar measurements for the "uranium star" CS 31082-001 have been reported by Aoki et al. (2003). These VMP and EMP stars are expected to have had essentially all of their Eu produced by the r-process in the early Galaxy; hence it is of some significance that the measured ratio $f(^{151}{\rm Eu}) = {}^{151}{\rm Eu}/(^{151}{\rm Eu} + {}^{153}{\rm Eu})$ is, within measurement error, equal to the value of this ratio in solar-system material, where $f(^{151}{\rm Eu}) \sim 0.5$. Aoki et al. (2003) have used similar techniques to study this ratio in the s-process-enhanced VMP stars LP 625-44 and CS 31062-050 and report that $f(^{151}{\rm Eu}) = 0.60$ and 0.55, respectively. This value, which is marginally higher than the ratio observed in the r-process-enhanced stars, is consistent with the predictions from AGB nucleosynthesis by Arlandini et al. (1999), who obtain, for their "best fit" and "classical" models of s-process material in the solar system, values of 0.54 and 0.59, respectively. Hence, at least potentially, one may have a tool for evaluation of the relative fraction of s- and r-processing that a given star has experienced during its nucleosynthesis history. This is of particular value for examination of stars that are thought to have incorporated contributions from both processes, the so-called r/s stars (see Section 4.5.4.).

## 4.3. Carbon-Enhanced Metal-Poor Stars

Recent observations of VMP candidates from the HK and HES prism surveys have revealed that on the order of 20% of stars with [Fe/H] $\leq -2.0$ (as determined from moderate-resolution follow-up spectra with the technique of Beers et al. 1999, or more recently with that of Rossi et al. 2005) exhibit large overabundances of carbon, i.e., [C/Fe] $> +1.0$.[1] As pointed out by Norris, Ryan & Beers (1997), the fraction of disk stars with near-solar metallicities that exhibit such large carbon overabundances is no more than a few percent. The carbon-enhancement phenomenon, which was first noticed in VMP stars by Beers, Preston & Shectman (1992), is clearly revealed by the presence of an abnormally strong CH G-band feature at 4300 Å (often accompanied by other molecular carbon features). Furthermore, over the metallicity range $-4.0 <$ [Fe/H] $< -2.0$, there exists an upper limit to the level of carbon enhancement amongst CEMP stars, at [C/H] $\sim -1.0$ (Rossi, Beers & Sneden 1999; Ryan 2003). This immediately suggests that at some early time in the Universe a significant amount of carbon was produced, in all likelihood by one of the following sources: (1) a primordial mechanism from massive stellar progenitors, (2) intrinsic internal production by low-mass stars of extremely low [Fe/H], or (3) extrinsic production of carbon by stars of intermediate mass, which can be prodigious manufacturers of carbon during their AGB stages, followed by mass transfer to a surviving lower-mass companion. It remains possible that all three sources have played a role.

The first alternative, in which the observed levels of carbon in at least some of the CEMP stars is primordial, or close to primordial, and was produced in the first generations of stars, receives some support from models of element production in zero-metallicity stars in the mass range 18–30 $M_\odot$ (Woosley & Weaver 1995). Indeed, J.H. Wise & T. Abel (submitted) appeal to the explosions of the very first (super-massive) stars that formed in the early Universe to account for the large amount of carbon found in studies of Lyman-alpha-forest clouds at high redshift (e.g., Songaila 2001). Inspection of high-resolution spectra for a large sample of CEMP stars may reveal other abundance signatures that could only arise from production in high-mass supernovae explosions.

The second possibility is that, early in the Universe, when there were few heavy elements present, unusually effective mixing episodes triggered at the time of helium core flash dredged up internally produced carbon and deposited it on the surfaces of low-mass stars (Fujimoto, Ikeda & Iben 2000; Schlattl et al. 2002; Weiss et al. 2004; Picardi et al. 2004). Detailed calculations of the predicted element abundance signatures in this scenario (other than for C, N, and O) are only now beginning to be explored (e.g., Suda et al. 2004). These predictions could be tested on the basis of high-resolution spectroscopic observations of CEMP stars. One might further expect that at least some low-mass stars that have had their carbon enhanced through this mechanism may exist as single objects, not as binaries; long-term radial velocity monitoring may reveal their existence.

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[1] We note that [Fe/H] might be overestimated by a few tenths of a dex when applying the technique of Beers et al. (1999) to carbon-enhanced stars (J. Cohen 2005, private communication), which could somewhat reduce the fraction of stars with [C/Fe] $> +1.0$ among stars with [Fe/H] $\leq -2.0$. Improved techniques employing ANNs and spectral modeling have already been developed and are presently being tested.

The final alternative is that intermediate-mass stars (in the mass range $2 \leq M_{\odot} \leq 8$) evolved quickly in the early Galaxy, and produced large amounts of carbon during their AGB evolution. If such stars are members of binary systems, under certain conditions a significant amount of this carbon-rich material could have been transferred to the long-lived companion, via roche-lobe overflow or a wind. The lower-mass companion is presently observed to be carbon-rich, whereas the higher-mass carbon-producing star is now a faint white dwarf (see, e.g., Lucatello et al. 2005). This is the same model that has been invoked to account for the observed elemental abundances and binarity properties of the more metal-rich subgiant CH stars, CH stars, and Ba stars (for additional discussion of this point, see S.G. Ryan, W. Aoki, J.E. Norris, & T.C. Beers, submitted). In this scenario, one would expect to be able to detect the presence of the binary system by identifying the tell-tale radial velocity variations of the visible companion (see, e.g., McClure 1984, McClure & Woodsworth 1990, Preston & Sneden 2001), although the long periods (up to 10 years or more) in some such binaries presents an observational challenge. In any case, because long-term radial velocity monitoring is crucial for constraining the origin of carbon in CEMP stars, observational programs targeting large samples of CEMP stars are underway.

## 4.4. s-Process–Enhanced Stars

Over the course of the past decade there has been tremendous progress in the development of models for the production of s-process nuclei, in particular for the site thought to be associated with the so-called main component of the s-process, the thermal-pulsing episodes in intermediate-mass AGB stars (see, e.g., Busso, Gallino & Wasserburg 1999; Herwig 2004a,b). In AGB stars, the dominant source of neutrons is likely to be the $^{13}C(\alpha, n)^{16}O$ reaction. In more massive stars, the reaction $^{22}Ne(\alpha, n)^{25}Mg$ is thought to play the dominant role, in particular for the production of the light s-process elements (the so-called weak component, see, e.g., Prantzos, Hashimoto & Nomoto 1990). Herwig (2005, this volume) provides a review.

Because of the (possibly) required presence of iron-peak seed nuclei for the operation of the s-process, the expectation is that there might be little or no evidence of element production from this source in the early Galaxy. However, large recent studies of metal-deficient stars have identified stars that exhibit clear s-process signatures with [Fe/H] as low as −2.6 (Simmerer et al. 2004). Sivarani et al. (2004) have discussed detailed observations of a CEMP star, CS 29497-030, that show clear evidence of the s-process, even at the low metallicity of [Fe/H] = −2.8. The lowest metallicity star known that exhibits an s-process signature is CS 22183-015, a CEMP star with [Fe/H] = −3.1 (Johnson & Bolte 2002). We caution, however, that the nature of the s-process at very low metallicities is still very uncertain; it is not even clear that the requirement of iron-peak seeds applies, as it appears to for intermediate and solar-metallicity stars.

A recent prediction of s-process nucleosynthesis models in AGB stars (Gallino et al. 1998; Goriely & Mowlavi 2000; Busso et al. 2001) is that one might expect efficient production of the heaviest elements, such as Pb, to occur in very metal-poor environments; the lack of seed nuclei leads to the very high neutron-to-seed ratios needed for its manufacture. Indeed, Aoki et al. (2000) reported the first detection of Pb in an s-process-rich VMP star, the CEMP-s star LP 625-44, with [Fe/H] $= -2.7$. This was followed shortly thereafter by the discovery of somewhat higher-metallicity stars ($-2.5 \leq$ [Fe/H] $\leq -1.5$) by Van Eck et al. (2001) that were more enriched in Pb than in any other element heavier than Fe. Such so-called lead stars now include more than 20 well-studied examples (see table 5 of Sivarani et al. 2004); many more are expected to be found in the near future. The most extreme [Pb/Fe] ratio reported to date is found for CS 29497-030, with [Pb/Fe] $= +3.5$, over 3000 times greater than the solar ratio of these two elements (Sivarani et al. 2004).

## 4.5. r-Process–Enhanced Stars

Recent comprehensive summaries of the nuclear physics and astrophysics of the r-process are provided by Truran et al. (2002), Qian (2003), and Cowan & Thielemann (2004). Here we concentrate on some of the questions that have arisen from the discovery and analysis of the r-process-enhanced, metal-poor stars.

### 4.5.1. THE r-II STARS

The prototype r-II star is CS 22892-052, an EMP star ([Fe/H] $= -3.1$) found in the HK survey. High-resolution spectra revealed that the strength of absorption features associated with the r-process, such as Eu II, were far greater than had been previously observed in giants of such low metallicity (McWilliam et al. 1995).

Sneden et al. (1996) showed that numerous other elements, including some never detected before in metal-poor stars (such as Tb, Ho, Tm, Hf, and Os), exhibited abundances, relative to iron, that were between 30 and 50 times greater than observed in the Sun ($+1.2 \leq$ [r-process/Fe] $\leq +1.6$). Even more remarkable, in this star as well as in other r-II and r-I stars that have been discovered since, the elemental abundances in the range $56 < Z < 76$ closely track a scaled solar-system r-process abundance pattern. The implications of this result are still the subject of discussion, but one appealing model is that, no matter what the astrophysical site of the "main" r-process, it has produced heavy elements with astounding consistency, from the earliest times in the Galaxy up to the formation of the Solar System.

During the course of the ESO Large Programme "First Stars" of Cayrel et al., high-resolution observations of the VMP ([Fe/H] $= -2.9$) giant CS 31082-001 revealed it to be an r-II star as well ([Eu/Fe] $= +1.6$, Cayrel et al. 2001). In contrast to CS 22892-052, CS 31082-001 is not strongly carbon-enhanced, immediately calling into question any causal connection between the enhancement of carbon and the r-process-enhancement phenomenon.

Interestingly, though [Eu/Fe] (and the ratios of other r-process elements relative to iron) were enhanced by a similar factor as observed in CS 22892-052, Hill et al. (2002) noted that the Th/Fe ratio was almost a factor of 3 higher than observed in

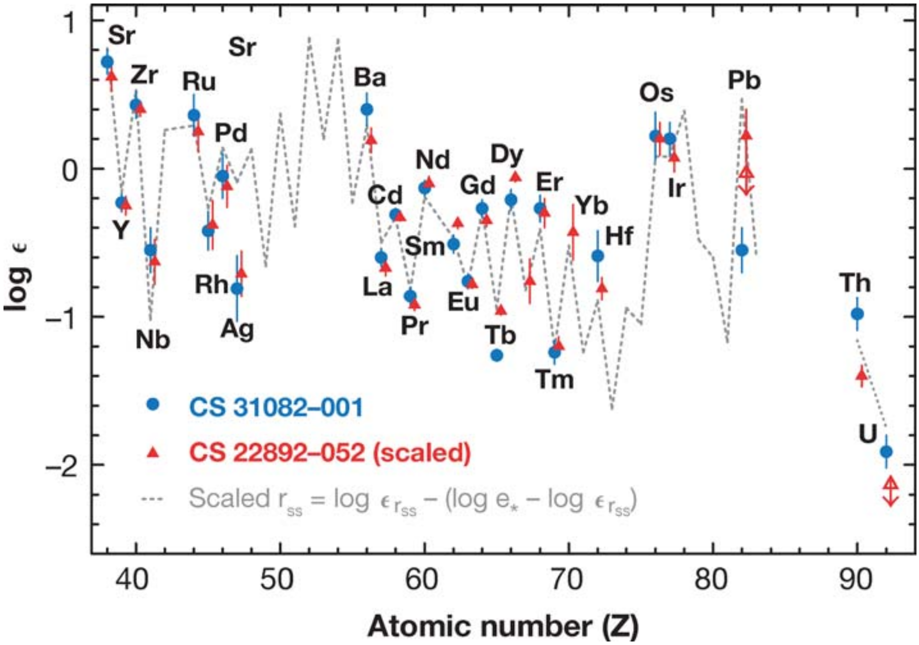

**Figure 4** Abundance patterns of the r-II stars CS 22892-052 and CS 31082-001. The abundances of the former star are taken from Sneden et al. (2003); those of CS 31082-001 are from Hill et al. (2002), with the exception of Os and Ir (Ivarsson et al. 2003) and Pb (Plez et al. 2004). The *dashed line* is a scaled solar-system r-process abundance pattern. Note that, for the great majority of elements, the patterns in these two stars are indistinguishable; the clear exceptions are the cases of Pb and Th.

CS 22892-052 (see Figure 4 for a comparison of the abundance patterns of these two stars), i.e., log (Th/Eu) = −0.22 as compared with log (Th/Eu) = −0.62 in CS 22892-052 (Sneden et al. 2003).

Honda et al. (2004a,b) reported on the discovery of one new r-I star (CS 30306-132; [Eu/Fe] = +0.85) and one r-II star (CS 22183-031; [Eu/Fe] = +1.2). CS 30306-132 is the second star known to exhibit an "actinide boost"—its Th/Eu ratio of log (Th/Eu) = −0.10 is even higher than the ratio observed in CS 31082-001.

Plez et al. (2004) measured a surprisingly low Pb abundance for CS 31082-001, log $\epsilon$ (Pb) = −0.55 ± 0.15 (see Figure 4). One consequence is that if the solar inventory of r-process elements is due to the same nucleosynthesis process that enriched CS 31082-001, the fraction of Pb in the solar system that has its origin in the r-process could be as low as a few percent, and therefore the remaining Pb must have been produced in the s-process. According to Plez et al. (2004), the Pb abundance in CS 31082-001 might be accounted for, almost in its entirety, from the summed decays of the radioactive actinides Th and U.

4.5.2. THE r-I STARS A handful of r-I stars have been noted in the literature; e.g., HD 115444 (Westin et al. 2000) and BD + 17° 3248 (Cowan et al. 2002). These stars appear to be, on the whole, at least twice as common as their extreme counterparts, the r-II stars. The r-I stars are not only useful for age determinations (see below), but they also provide valuable information on the consistency of the pattern of heavy r-process elements from star-to-star, as is seen for r-II stars.

4.5.3. COSMO-CHRONOMETRY Ages of astrophysical objects (including the Universe itself) are often considered the "Holy Grail" of astronomers. A great deal of effort over the past decades has been made to refine age estimates for stars, clusters of stars, and stellar populations (e.g., Krauss & Chaboyer 2003).

One recent technique has generated a great deal of interest: the use of r-process-enhanced VMP and EMP stars with measured abundances of the radioactive-decay elements Th and U to place limits on the age of individual stars [more appropriately, on the time interval that has passed since the production of these elements by the progenitor object(s) of these stars], and hence on the Galaxy and the Universe. See the recent review of Kratz et al. (2004) for additional comments on the cosmo-chronometry technique.

This approach, pioneered by Butcher (1987), received renewed interest from the measurement of Th in CS 22892-052 (Sneden et al. 1996) which led to the use, by a number of authors, of the Th/Eu chronometer to estimate the age of this star (Cowan et al. 1997, 1999; Sneden et al. 1996). Sneden et al. (2003) employed new calculations for the Th/Eu production ratio, and improved measurements of these elements, to determine an age of 12.8 $\pm$ 3 Gyr for CS 22892-052, consistent with inferences of the age of the Universe from the Wilkinson Microwave Anisotropy Probe (WMAP; Bennett et al. 2003), 13.7 $\pm$ 0.2 Gyr.

Cosmo-chronometry requires knowledge of the production ratio of the elements involved, which depends ultimately on detailed understanding of the operation of the r-process itself (a nucleosynthesis path that is not yet firmly associated with a given astrophysical site), as well as on uncertain nuclear physics constraints (see, e.g., Schatz et al. 2002, Wanajo et al. 2002).

In addition, for Th chronometry, abundance errors of only 10% lead to an uninterestingly large error on the age estimate, roughly 5 Gyr, and hence very accurate abundances are required for useful age determinations. Furthermore, the high Th/Eu ratios, observed in CS 31082-001 $\log(\mathrm{Th/Eu}) = -0.22$ and CS 30306-132 ($\log(\mathrm{Th/Eu}) = -0.10$), make the use of this chronometer questionable, a limitation that also applies to alternative chronometer pairs involving the actinides Th or U in combination with lighter elements ($Z \leq 70$). Recent theoretical r-process calculations yield a production ratio of $\log(\mathrm{Th/Eu})_0 = -0.35$ (Sneden et al. 2003); hence it would follow from Th/Eu cosmo-chronometry that both of these stars have a negative age.

Because of the low carbon abundance of CS 31082-001, it was possible for the first time in a metal-deficient star to detect not only thorium, but also uranium (Cayrel et al. 2001), a potentially much more useful chronometer than Th (Wanajo et al. 2002). Cayrel et al. (2001) suggested that an improved chronometer could be obtained from comparison of the ratio of U and Th, arguing that nuclear physics uncertainties in their production are minimized because they lie so close to one another in the periodic table (separated only by Pa).

As a result of the shorter half-life of $^{238}$U (4.47 Gyr as compared with 14.05 Gyr for $^{232}$Th), abundance errors of $\sim$10% results in derived age uncertainties on the order of 2 Gyr, which are still interesting. Indeed, the desire to make use of the U/Th chronometer is one of the driving forces behind intense searches for additional stars in which both species are measurable. The HERES survey (see Section 3.4) has already resulted in the discovery of the second VMP star with clearly-detected U and Th, CS 29497-004. High signal-to-noise, high-resolution observations have already been obtained for this star, and an analysis will be reported by Hill and colleagues (V. Hill, N. Christlieb, T.C. Beers, & P.S. Barklem, in preparation).

#### 4.5.4. THE r/s STARS

There are currently three stars known to be enriched in r- and s-process elements: CS 22948-027, CS 29497-034 (Hill et al. 2000; Preston & Sneden 2001; Aoki et al. 2002c) and HE 2148−1247 (Cohen et al. 2003). Cohen et al. proposed a scenario for explaining the abundance pattern of HE 2148−1247, described in more detail by Qian & Wasserburg (2003). They suggest that the star is a member of a binary system (and in fact, the star shows significant radial variations) in which the former primary went through the AGB phase. In this stage, carbon and s-process elements were dumped onto the surface of HE 2148−1247 via mass transfer. The former primary then evolved into a white dwarf. Mass transfer then occurred in the reverse direction, i.e., from HE 2148−1247 to the white dwarf, leading in turn to an accretion-induced collapse of the white dwarf into a neutron star. Subsequent r-process nucleosynthesis is then presumed to occur in a neutrino-driven wind of the neutron star, and the nucleosynthesis products contaminate the surface layers of the star that is observed today.

An alternative scenario has been proposed by Zijlstra (2004). He argues that the strong metallicity dependence of mass loss during the AGB phase leads to a steeper initial-final mass relation for low-metallicity stars; that is, for a given initial mass the final mass is higher for metal-poor stars. Therefore, the core of, e.g., an EMP star with [Fe/H] $= -3.0$ having an initial mass of 4 $M_{\odot}$, would reach the Chandrasekhar mass, leading to a "Type 1.5 supernova" (Iben & Renzini 1983). In such a supernova, r-process nucleosynthesis might have occurred, and the surface of the companion star observed today could have been polluted with the elements that were produced.

Wanajo and colleagues (S. Wanajo, K. Nomoto, N. Iwamoto, Y. Ishimaru, & T.C. Beers, submitted) consider a similar model but suggest that a slightly more massive (i.e., 8–10 $M_{\odot}$) companion has polluted the surfaces of the r/s stars. In this companion, s-process nucleosynthesis through He shell flashes could have been taken place during the AGB phase, and r-process nucleosynthesis could have occurred later during the collapse and explosion of the O–Ne–Mg core.

Although the above scenarios are still quite speculative, it is clear that r/s-stars may provide important clues for identifying at least one possible astrophysical site of the r-process. More examples of such stars have been identified in the HERES effort and are currently being analyzed.

4.5.5. OPEN QUESTIONS The discovery of r-process-enhanced, metal-poor stars has focused attention on a number of critical questions concerning the astrophysical sites involved in the formation of the r-process elements. These questions include the following:

- What is the frequency of r-I, r-II, and r/s stars as a function of metallicity? Whereas the three r-II stars reported in the literature all have [Fe/H] $\sim -3.0$, the r-I (and also the r/s stars) appear to cover a wider range in metallicity, extending from [Fe/H] $\sim -3.0$ up to [Fe/H] $\sim -2.0$. This suggests that large enhancements with pure r-process elements might be associated with the earliest r-process-generating events.
- What is the distribution of r-process enhancements for r-I, r-II, and r/s stars? This question (combined with the one above) is essentially the same as put forward by Wasserburg & Qian (2000) and Fields, Truran & Cowan (2002), who sought to test phenomenological models for the origin of the r-process.
- How stable is the pattern of r-process-element abundances in the range $56 < Z < 76$? A quantitative answer to this question, based on a large sample of stars, should provide important constraints on models of the astrophysical production of r-process elements.
- What is the range of abundances exhibited by r-process elements in the range $40 < Z < 50$? To better constrain the origin of these elements, and to establish whether their production is consistent with a hypothesized weak r-process, or other alternatives (Travaglio et al. 2004), the star-to-star scatter of the abundances of the light r-process elements must be quantified.
- What is the range of r-process-enhancement for the third r-process-peak elements, $Z > 76$, and for the actinides Th and U? This question goes to the very heart of the application of cosmo-chronometers involving the actinides, as well as their decay products.

Answers to all the above questions are required to place strong constraints on the operation of the early r-process(es) and to exploit the information that such constraints provide on their astrophysical site(s). As described in Section 3.4, techniques that directly address these questions are now available and are being used to increase the total sample of r-II stars by at least an order of magnitude.

## 4.6. Light Elements

Recent excellent reviews on the measurement and astrophysical importance of the light elements (Li, Be, B) in metal-poor stars can be found in Boesgaard (2004), Lambert (2005), and Prantzos (2005). Here we only highlight a few issues relating to Li.

Over two decades ago Spite & Spite (1982) demonstrated that, below [Fe/H] $= -1.0$, the measured abundance of Li (which is dominated by the isotope $^7$Li) in "warm" metal-poor stars near the main-sequence turnoff remains remarkably constant, at a value near $\log \epsilon\,(\mathrm{Li}) = 2.0$. This so-called Spite plateau was immediately recognized by these authors, and many since, as likely to be associated with the primordial Li produced during the Big Bang, preserved (or nearly so) in the atmospheres of metal-poor stars. Full understanding of the implications of the Spite plateau remains an active enterprise to this day.

One central problem is how to resolve the apparent disagreement of the primordial Li abundance, as inferred from the recent determination of $\Omega_b h^2$ by WMAP (Bennett et al. 2003) and standard Big Bang nucleosynthesis (SBBN) models, with the primordial Li abundance inferred from measurements in metal-poor stars. Coc et al. (2004) derive $\log \epsilon\,(\mathrm{Li}) = 2.62 \pm 0.05$ from the WMAP results using SBBN, whereas Ryan et al. (2000) infer $\log \epsilon\,(\mathrm{Li}) = 2.09^{+0.19}_{-0.13}$ from an analysis of 23 metal-poor stars near the main-sequence turnoff in the metallicity range $-3.3 <$ [Fe/H] $< -2.2$, taking into account an increase of the Li abundance with [Fe/H] of $0.118 \pm 0.023$ dex per dex (Ryan, Norris & Beers 1999).

Coc et al. (2004) investigated the possible influence of inaccurate reaction rates being used in SBBN calculations on predictions of the primordial Li abundance. They identified the reaction $^7\mathrm{Be}(d, p)2\,^4\mathrm{He}$ as a possible candidate for the solution of the problem. This reaction competes with $^7\mathrm{Be}(n, p)^7\mathrm{Li}$ and therefore influences $^7$Li production. If the rate of the former reaction would be larger by a factor of ~300 than previously assumed, the predicted $^7$Li would be a factor ~2.5 lower (see figure 4 of Coc et al. 2004), and the discrepancy would vanish. In fact, there are currently no experimental data at SBBN energies available for that reaction.

Because of the high quality of recent measurements one can exclude the possibility that the discrepancy is due to random observational errors, given that the observed scatter around the $^7$Li plateau is extremely small. For instance, Ryan, Norris & Beers (1999) find a dispersion of only $\sigma = 0.031$ dex about their trend line. The small scatter around the $^7$Li plateau and the presence of a $^6$Li plateau (see below) make it difficult to conceive of a mechanism that might have uniformly depleted the primordial abundance by about a factor of 3 (see the review of Lambert 2005 for a detailed discussion). Systematic observational errors, due to the simplified assumptions made in classical 1D model atmosphere analyses (i.e., plane-parallel geometry, hydrostatic equilibrium, convection according to mixing-length theory, line formation in LTE conditions, etc.), also seem to be ruled out. Asplund, Carlsson & Botnen (2003) show that 1D LTE and 3D NLTE analyses agree to within ~0.1 dex. The use of improved calculations for inelastic collisions between H and Li atoms in 1D and 3D NLTE calculations yields 0.05–0.10 dex lower Li abundances (Barklem, Belyaev & Asplund 2003), increasing the disagreement between WMAP/SBBN and metal-poor-star Li abundances.

Meléndez & Ramírez (2004) analyzed 41 stars, using equivalent widths from the literature, and a newly suggested temperature scale for metal-poor stars. They obtained an Li-plateau abundance of $\log\epsilon\,(\mathrm{Li}) = 2.37 \pm 0.06$, which is closer to the value inferred from the WMAP results and SBBN but still leaves a difference of approximately a factor of 2. Fields, Olive & Vangioni-Flam (2005) have pointed out that if the (substantially warmer) temperature scale of Meléndez & Ramírez (2004) is correct, it also implies a significant increase in the derived abundances of B, as well as O, presenting a severe challenge to models of galactic cosmic ray nucleosynthesis and galactic chemical evolution.

An increase of the $^7$Li abundance with [Fe/H] would indicate that $^7$Li might have been produced, e.g., by galactic cosmic-ray spallation and/or supernovae $\nu$ processes in operation in the early Galaxy (Ryan et al. 2000). The slope found by Ryan, Norris & Beers (1999) has recently been independently confirmed by M. Asplund, P.E. Nissen, D.L. Lambert, F. Primas, & V. Smith (submitted), using very high-quality data ($S/N > 400$ per pixel and $R = 125{,}000$) obtained with VLT/UVES. For 24 stars in the range $-3.0 <$ [Fe/H] $< -1.0$ they find a slope of $0.10 \pm 0.01$ dex per dex, i.e., almost identical to the result of Ryan, Norris & Beers (1999). On the other hand, Meléndez & Ramírez (2004), using their new temperature scale, do not find a trend in the abundance of Li with [Fe/H] (Fields, Olive & Vangioni-Flam 2005 discuss reasons why this is not unexpected, given the details of the Meléndez & Ramírez analysis). An analysis of 23 VMP main-sequence turnoff stars observed in the course of the VLT/UVES First Stars program is in progress (P. Bonifacio, P. Molaro, R Cayrel, M. Spite, T. Beers, et al., in preparation) and hopefully might provide some insight.

The most metal-poor stars near the main-sequence turnoff can potentially provide strong constraints on the slope of the Li abundance. Unfortunately, it seems that in the most iron-deficient star known, HE 1327−2326 ($[\mathrm{Fe/H}]_{\mathrm{NLTE}} = -5.4$; Frebel et al. 2005; W. Aoki, A. Frebel, N. Christlieb, J.E. Norris, T.C. Beers, et al., in preparation) Li appears to have been depleted by a presently unknown mechanism. Li I 6707 Å is not detected in a high-resolution Subaru/HDS spectrum, yielding an upper limit for the lithium abundance of $\log\epsilon\,(\mathrm{Li}) < 1.6$ (Frebel et al. 2005; W. Aoki, A. Frebel, N. Christlieb, J.E. Norris, T.C. Beers, et al., in preparation), about 0.5 dex below the primordial Li abundance of $\log\epsilon\,(\mathrm{Li}) = 2.09^{+0.19}_{-0.13}$ (Ryan et al. 2000).

It is noteworthy that at least the absence of an intrinsic $^7$Li abundance scatter is now indisputable; all three aforementioned published studies agree on this issue. However, whereas Ryan et al. and Asplund et al. find $\sigma \lesssim 0.03$ dex, Meléndez & Ramírez observe a scatter that is about a factor of 2 higher. According to these authors, however, this larger scatter is fully accounted for by uncertainties in effective temperatures and measurements of equivalent widths.

M. Asplund, P.E. Nissen, D.L. Lambert, F. Primas, & V. Smith (submitted) detected $^6$Li in 10 metal-poor turnoff stars (see also Asplund et al. 2001). They find a plateau of $^6$Li at a level of ~1.3 dex below the Spite plateau (see Figure 5). No detectable amount of $^6$Li is produced in SBBN, therefore other origins must be

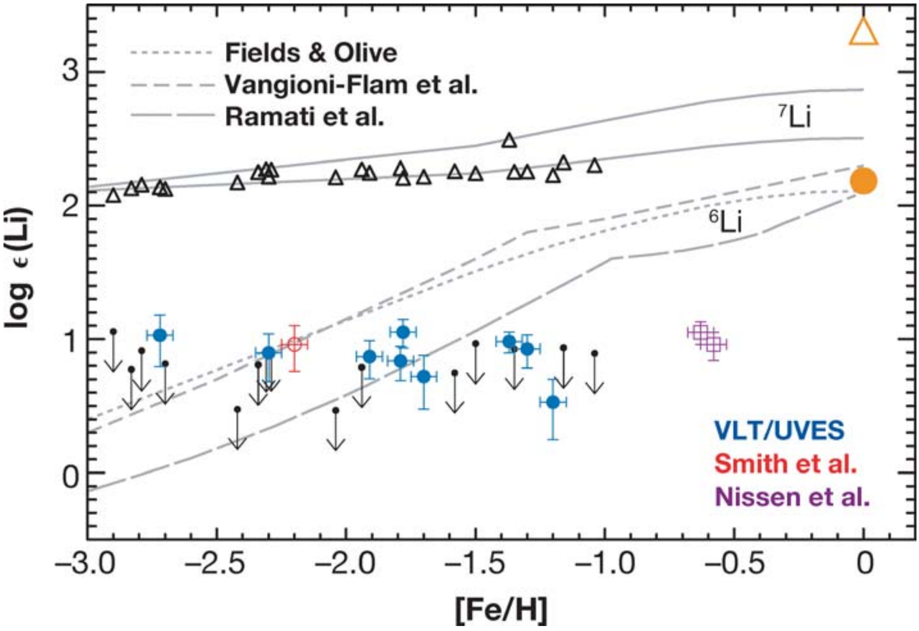

**Figure 5** $^7$Li (*triangles*) and $^6$Li (*filled circles*) measurements of M. Asplund, P.E. Nissen, D.L. Lambert, F. Primas, & V. Smith (submitted). *Arrows* indicate upper limits. Note the small, but statistically significant, increase of $^7$Li abundance with [Fe/H] and the existence of a plateau of $^6$Li. The *large symbols* at [Fe/H] = 0 are the solar (meteoritic) values. The lines indicate predictions of various production models [for details see M. Asplund, P.E. Nissen, D.L. Lambert, F. Primas, & V. Smith (submitted)].

sought. Possibilities include nonstandard BBN, or pre-galactic fusion of $^4$He (see Prantzos 2005 for details and references).

## 4.7. Abundances and Scatter of Heavy Elements in VMP Stars

In the pioneering works of McWilliam et al. (1995) and Ryan, Norris & Beers (1996), elemental abundances of 33 and 19 metal-poor stars, respectively, were determined on the basis of high-resolution spectra obtained with 2.5 to 4 m-class telescopes. McWilliam (1997) reviews the abundance trends found in these studies and discusses consequences for galactic chemical evolution (see also Wheeler, Sneden & Truran 1989).

The ESO Large Programme "First Stars" carried out with VLT/UVES has yielded a (continuing) series of very influential papers. Very high-quality data (i.e., $R = 45{,}000$, $S/N = 100$–200 per pixel and wavelength coverage 3300–10,000 Å) of ~70 stars have been obtained (e.g., Depagne et al. 2002; François et al. 2003; Cayrel et al. 2004; Spite et al. 2005). A similar observational strategy is adopted in the 0Z (zero Z) project carried out with Keck/HIRES (and since recently also Magellan/MIKE), albeit with slightly lower $S/N$ and less complete wavelength coverage (see Cohen et al. 2002, 2004; Carretta et al. 2002).

The new high-quality data enable a detailed investigation of the abundance trends and the scatter around these trends at low metallicities. The latter is a particularly important observable, because it can be used to assess the degree of mixing of the interstellar medium (ISM) with heavy elements at a given epoch, as traced by [Fe/H] or [Mg/H] (see, e.g., Argast et al. 2000).

Cayrel et al. (2004) analyzed 35 VMP giants and found abundance trends that agree well with those known from the work of McWilliam et al. (1995) and Ryan, Norris & Beers (1996). However, the scatter of several abundance ratios (e.g., [Mg/Fe], [Ca/Fe], [Cr/Fe], and [Ni/Fe]) is much smaller than reported by previous studies and is close to, or even smaller, than a tenth of a dex. In the case of [Cr/Fe] it is as small as 0.05 dex (see Figure 6), consistent with zero, given the likely errors associated with the observations and analysis. Small abundance scatters were also found by Cohen et al. (2004) in 28 dwarfs observed with Keck/HIRES and for Mg in a sample of 23 turnoff stars observed with AAT/UCLES and reported by Arnone et al. (2004).

One possible conclusion is that, in VMP stars, we appear not to observe the nucleosynthesis products of only a few or even single SN II, as has been previously thought (e.g., Audouze & Silk 1995; Shigeyama & Tsujimoto 1998; Tsujimoto, Shigeyama & Yoshii 2000; Prantzos 2005), but rather, the integrated yields of many SNe. The observed low scatter could then be explained by a well-mixed ISM.

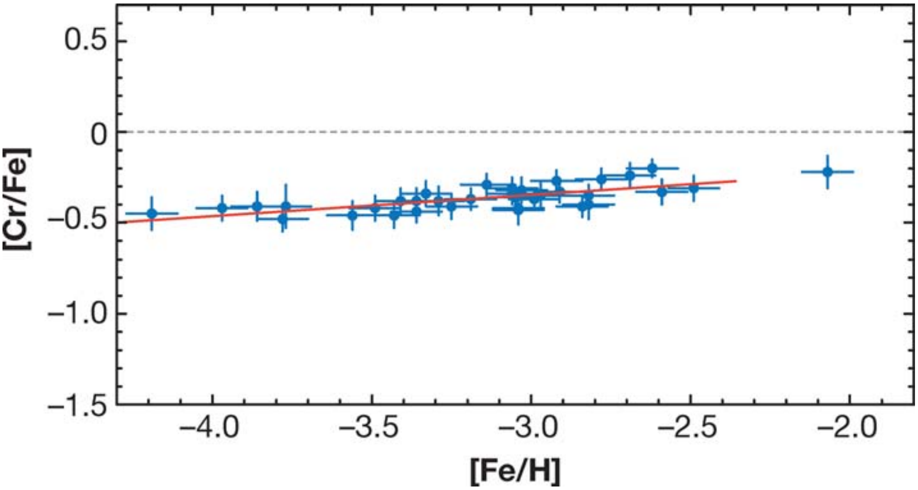

**Figure 6** [Cr/Fe] as a function of [Fe/H] for 35 VMP giants from the HK survey observed with VLT/UVES (Cayrel et al. 2004). The error bars are one-sigma estimates. Note the extremely small scatter about the trend line.

Nomoto et al. (2005), on the other hand, consider an unmixed ISM and formation of the next generation of stars from gas clouds that were enriched by single hypernovae with a range of explosion energies. Because of tight correlations between the explosion energy and the swept-up hydrogen mass as well as abundance ratios such as [Cr/Fe] and [Zn/Fe], it seems possible to reproduce the observed abundance trends as well as the small observed scatter around these trends.

Karlsson & Gustafsson (2005) also reproduce the low star-to-star scatter of abundance ratios in their inhomogenous model of chemical evolution by assuming that only SNe in a limited mass range contributed to the enrichment of the gas clouds from which the most metal-poor stars formed.

In all of the above mentioned observational studies only a few EMP stars with [Fe/H] $< -3.5$ were investigated; hence it is difficult to quantify the abundance scatter in this metallicity range. However, from the variety of abundance patterns seen in individual stars (see Table 4), it appears that we do observe the results of only a few nucleosynthesis events. A homogeneous analysis of a larger sample of stars with [Fe/H] $< -3.5$ is needed to clarify this issue. Such an effort is currently underway, based on data obtained with Subaru/HDS (W. Aoki, A. Frebel, N. Christlieb, J.E. Norris, T.C. Beers, et al., in preparation).

## 5. THE LOWEST METALLICITY STARS

The most metal-poor stars probe the earliest phases of galactic chemical evolution, and considerable effort has been invested to increase the samples of such stars by means of wide-angle surveys and to study the identified stars in detail. Currently there are 12 stars known to have [Fe/H] $< -3.5$, according to published high-resolution spectroscopic analyses. We summarize their stellar parameters and abundances of key elements in Table 4 and discuss some of the most important stars below. A recent review on these and related topics is provided by Norris (2004).

We note that, strictly speaking, many of the stars at [Fe/H] $< -3.5$ are not metal poor in terms of their mass fractions, $Z$, of the elements heavier than He, because they can have large overabundances of C, N, and O. These stars are perhaps more correctly referred to as heavy-element deficient rather than metal poor. The fact that 5 of the 12 (40%) currently known stars with [Fe/H] $< -3.5$ are carbon enhanced, including the only two known HMP stars, is surely of fundamental importance. Consideration of the full implications of this result awaits an expansion of the sample of the most metal-poor stars by (at least) a factor of 2.

### 5.1. CNO- and Mg/Si-Enhanced Stars

Two of the stars listed in Table 4, CS 22949-037 and CS 29498-043, share remarkably similar abundance patterns, characterized by large overabundances, not only of C, N, and O, but also of Mg and Si (see Figure 7). Indeed, on the basis of the measurements to date, it appears that most of the elements lighter than Ca

**TABLE 4** Elemental abundances of all stars known to have [Fe/H] $<-3.5$ from published analyses based on high-resolution spectroscopy

| Star | $T_{\mathrm{eff}}$ | Log *g* | [Fe/H] | [C/Fe] | [N/Fe] | [O/Fe] | [Na/Fe] | [Mg/Fe] | [Sr/Fe] | [Ba/Fe] | Comment | Refs |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HE 1327−2326 | 6180 | 3.7 | −5.4 (NLTE) | 4.1 (CH) | 4.4 (NH) | <4.0 (OH) | 2.2 | 1.7 | 0.9 | <1.5 | | 10 |
| | | 4.5 | −5.5 (NLTE) | 3.9 (CH) | 4.1 (NH) | <3.7 (OH) | 2.3 | 1.7 | 1.2 | <1.7 | | 10 |
| HE 0107−5240 | 5100 | 2.2 | −5.2 (NLTE) | 3.8 (CH) | 2.7 (CN) | 2.4 (OH) | 0.9 | 0.3 | <−0.4 | <0.9 | | 6, 3 |
| | | | | 4.1 (C2) | 2.4 (CN) | | | | | | | 6 |
| CD −38° 245 | 4800 | 1.5 | −4.2 | <−0.3 (CH) | 1.5 (NH) | | −0.1 | 0.2 | | | | 5, 16 |
| | 4900 | 2.0 | −4.0 | | | 0.9 (OH) | | | | | | 3 |
| | 4900 | 1.7 | −4.1 | | | | −0.1 | 0.3 | −0.7 | −0.7 | | 9 |
| | 4850 | 1.8 | −4.0 | <0.0 (CH) | 1.2 (NH) | | | 0.5 | −0.7 | −0.9 | | 13, 14 |
| G 77-61 | 4000 | 5.3 | −4.0 | 2.6 (CN) | 2.6 (CN) | | 0.6 | 0.5 | <0.0 | <1.0 | | 15 |
| CS 22885-096 | 5050 | 2.6 | −3.8 | 0.2 (CH) | 0.7 (NH) | | −0.1 | 0.2 | | | | 5, 16 |
| | 4900 | 2.0 | −4.0 | | | | 0.0 | 0.5 | −1.5 | −1.0 | | 9 |
| | 5050 | 1.9 | −3.7 | 0.6 (CH) | | | | 0.5 | −1.6 | −1.4 | | 13 |
| | | | | | <0.6 (NH) | | | | | | | 14 |
| CS 22949-037 | 4900 | 2.5 | −3.5 (NLTE) | | | 3.1 (OI, NLTE)<br>2.0 ([OI], NLTE) | | 1.2 (NLTE) | | | | 11 |
| | 4900 | 1.5 | −4.0 | 1.2 (CH) | 2.6 (CN) | 2.0 ([OI]) | 1.4 | 1.6 | | | | 5 |
| | | | | | 2.7 (NH) | | | | | | | 16 |
| | 4900 | 1.5 | −3.9 | 1.2 (CH) | 2.6 (CN) | 2.0 ([OI]) | 2.1 | 1.6 | 0.3 | −0.6 | | 8 |
| | 4900 | 1.7 | −3.8 | 1.1 (CH) | 2.7 (CN) | | | 1.2 | 0.1 | −0.8 | | 13 |
| | | | | | 2.3 (NH) | | | | | | | 14 |

(*Continued*)

**TABLE 4** (*Continued*)

| Star | $T_{\mathrm{eff}}$ | Log *g* | [Fe/H] | [C/Fe] | [N/Fe] | [O/Fe] | [Na/Fe] | [Mg/Fe] | [Sr/Fe] | [Ba/Fe] | Comment | Refs |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CS 22876-032A | 6300 | 4.5 | −3.7 | | | | | 0.5 | <−0.7 | <0.4 | DLSB | 12 |
| HE 0218−2738 | 6550 | 4.3 | −3.5 | | | | | 0.1 | −0.4 | | DLSB | 4, 7 |
| BS 16467-062 | 5200 | 2.5 | −3.8 | 0.3 (CH) | <0.9 (NH) | | | −0.2 | 0.2 | | | 5, 16 |
| | 5100 | 1.9 | −4.0 | | | | | 0.5 | <−2.1 | <−0.5 | | 9 |
| CS 22172-002 | 4800 | 1.3 | −3.9 | 0.0 (CH) | 0.6 (NH) | 1.0 ([OI]) | −0.4 | 0.2 | | | | 5, 16 |
| | 4800 | 1.3 | −3.8 | | | | −0.4 | 0.2 | −1.5 | −1.4 | | 9 |
| | 4900 | 2.0 | −3.6 | 0.1 (CH) | | | | 0.4 | −1.2 | −1.2 | | 13 |
| CS 22968-014 | 4850 | 1.7 | −3.6 | 0.3 (CH) | 0.6 (NH) | 0.9 ([OI]) | −0.4 | 0.2 | | | | 5, 16 |
| CS2 29498-043 | 4400 | 1.5 | −3.5 (NLTE) | | | 3.0 (OI, NLTE)<br>2.5 ([OI], NLTE) | | 1.1 (NLTE) | | | 11 | |
| | 4600 | 1.2 | −3.5 | 2.1 (C2) | 2.3 (CN) | 2.4 ([OI]) | 1.5 | 1.8 | −0.5 | −0.5 | | 2 |
| | | | | | | 2.9 (OI) | | | | | | 2 |
| | 4400 | 0.6 | −3.8 | 1.9 (C2) | 2.3 (CN) | | | 1.8 | −0.4 | −0.5 | | 1 |

Note that the values listed in this table were derived with 1D-model atmospheres. The abundances derived from molecular features (i.e., CH, OH, CN, and NH) may systematically be too high by up to 0.5 dex (see Asplund, this volume). Abundances were determined with NLTE analyses where indicated.

References: 1–Aoki et al. (2002b); 2–Aoki et al. (2004); 3–Bessell, Christlieb & Gustafsson (2004); 4–Carretta et al. (2002); 5–Cayrel et al. (2004); 6–Christlieb et al. (2004); 7–Cohen et al. (2002); 8–Depagne et al. (2002); 9–François et al. (2003); 10–Frebel et al. (2005); 11–Israelian et al. (2004); 12–Norris, Beers & Ryan (2000); 13–Norris, Ryan & Beers (2001); 14–Norris et al. (2002); 15–Plez & Cohen (2005); 16–Spite et al. (2005).

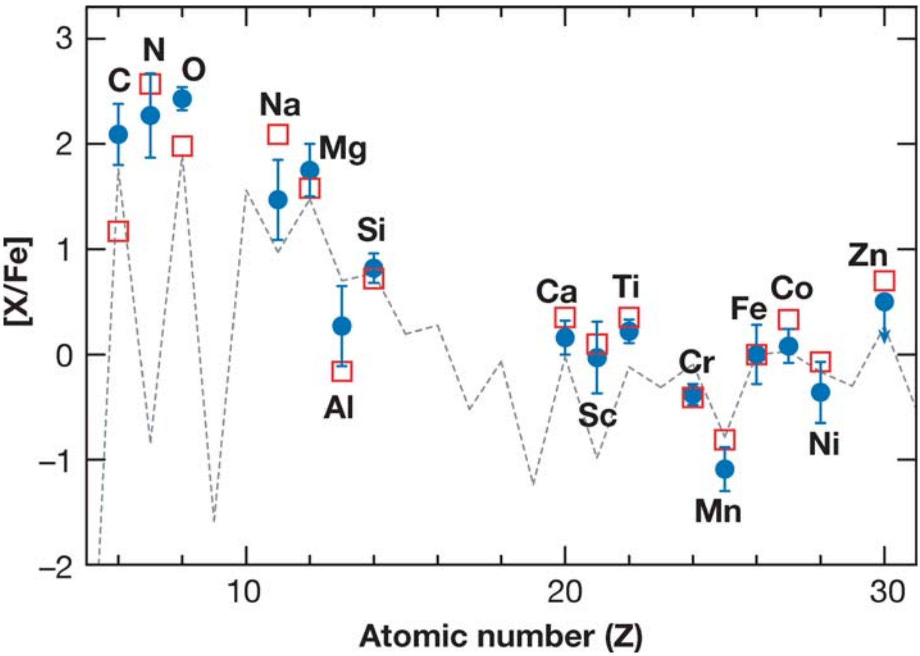

**Figure 7** Elemental abundances patterns, as a function of atomic number, for CS 29498-043 (*filled circles*, from Aoki et al. 2004), and CS 22949-037 (*open squares*, from Depagne et al. 2002). The *dashed line* is the abundance pattern predicted by Umeda & Nomoto (2003), based on a "low-energy" SN model with mixing and fallback. From Aoki et al. 2004 with permission.

in these stars are overabundant, as compared with "normal" EMP stars, such as CD −38° 245 and CS 22885-096 (Aoki et al. 2002b, 2004; Israelian et al. 2004). It is of some interest that neither of these stars exhibit radial velocity variations that might indicate membership in a binary system, although further monitoring is surely warranted.

Norris, Ryan & Beers (2001) discussed the role that very massive ($M > 200\,M_\odot$) Population III stars exploding as pair-instability supernovae (Fryer, Woosley & Heger 2001) might have played in pre-enriching the gas cloud from which CS 22949-037 formed. They concluded that although the process of enrichment of the ISM with the nucleosynthesis products of such objects has not yet been studied, they might provide a viable explanation for the abundance pattern of CS 22949-037, considering that large amounts of carbon and nitrogen are produced and that the predicted C/N ratio agrees well with that observed in CS 22949-037. Norris et al. also considered partial ejection of supernova mantles, as discussed by Woosley & Weaver (1995), for explaining the abundance pattern of CS 22949-037.

Depagne et al. (2002) argued that the observed abundance pattern of CS 22949-037 cannot be well reproduced by the yields of pair-instability supernovae. In particular, the observed odd/even effect is much smaller than predicted in such models, and the observed Zn abundance is too high ([Zn/Fe] = +0.7). Depagne et al. therefore considered SN II of much lower mass, $M \sim 35\,M_\odot$, in which all elements heavier than Si fall back onto the (presumed) black-hole remnant due to low explosion energy. They obtained a good fit of the abundance pattern, with the exception of a too-low predicted N abundance. However, N might have been produced in CS 22949-037 by the CNO cycle, as indicated by a carbon isotopic ratio close the CNO cycle equilibrium value.

Models of zero-metallicity, low-explosion-energy SN II, with mixing and fall-back, in the mass range 25–30 $M_\odot$ were also successfully employed by Umeda & Nomoto (2003) to explain the abundance patterns of CS 22949-037 as well as for HE 1327−2326 (for the latter star see Section 5.2). Given the striking similarity of the abundance pattern of CS 29498-043 to CS 22949-037, a similar model surely could apply to this star as well.

## 5.2. Hyper Metal-Poor Stars

There are currently two stars known to be heavy-element deficient by a factor of 100,000 or more with respect to the Sun: HE 0107−5240, a giant with $[\mathrm{Fe/H}]_{\mathrm{NLTE}} = -5.3$ (Christlieb et al. 2002, 2004), and HE 1327−2326, a subgiant or dwarf with $[\mathrm{Fe/H}]_{\mathrm{NLTE}} = -5.4$ (Frebel et al. 2005; W. Aoki, A. Frebel, N. Christlieb, J.E. Norris, T.C. Beers, et al., in preparation),[2] which we refer to as HMP stars. More than a decade ago, the dwarf carbon star G 77-61 was claimed to exhibit $\log\epsilon\,(\mathrm{Fe}) = 2.0$ (Gass, Wehrse & Liebert 1988). Adopting a solar iron abundance of 7.45 dex (Asplund et al. 2000), as was done in the analyses of the other two aforementioned stars, yields [Fe/H] = −5.5 for G 77-61. A recent re-analysis of this star, based on a high-quality Keck/HIRES spectrum, has shown that its metallicity is considerably higher, [Fe/H] = $-4.03 \pm 0.15$ (Plez & Cohen 2005).

### 5.2.1. THE ABUNDANCE PATTERNS OF HMP STARS

The abundance patterns of HE 0107−5240 (Christlieb et al. 2002, 2004; Bessell, Christlieb & Gustafsson 2004) and HE 1327−2326 (Frebel et al. 2005; W. Aoki, A. Frebel, N. Christlieb, J.E. Norris, T.C. Beers, et al., in preparation) are characterized by huge excesses of carbon and nitrogen with respect to iron and other heavy elements (see Table 4 and Figure 8). Both stars have [C/Fe] ∼ +4, and the abundances of Ca, Ti, and Fe relative to hydrogen are roughly the same.

However, whereas HE 0107−5240 has [N/Fe] = +2.3 to +2.6, HE 1327−2326 has an even higher nitrogen overabundance, [N/Fe] ∼ +4.1 or even [N/Fe] ∼ +4.4, depending on whether it is a dwarf or a subgiant. That is, in HE 1327−2326

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[2] Note that the NLTE corrections for the Fe I abundances of HE 0107−5240 and HE 1327−2326 used here have been determined with different methods. In particular, the assumptions on the efficiency of hydrogen collisions differ. According to Asplund (2004, private communication), NLTE corrections of ∼0.2 dex have to be applied to both stars, yielding $[\mathrm{Fe/H}]_{\mathrm{NLTE}} = -5.2$ for HE 0107−5240.

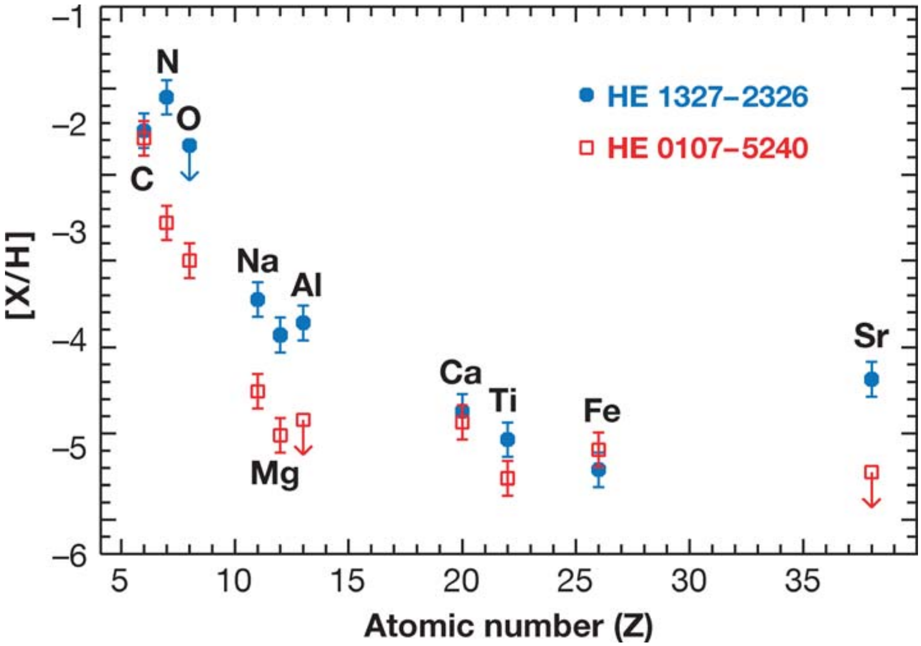

**Figure 8** Comparison of the abundance patterns of HE 0107−5240 and HE 1327−2326. Abundances determined with 1D stellar model atmospheres are shown. NLTE corrections were applied to the abundances of Na, Mg, Al, Fe, Sr, and Ba. For HE 1327−2326 we plot the abundances for the subgiant-branch stellar parameters of the star, i.e., $T_{\mathrm{eff}} = 6180$ K and $\log g = 3.7$. From Frebel et al. (2005) with permission.

the ratio of C/N is about 2, whereas it is 40–150 in HE 0107−5240, depending on which indicator is used for the carbon abundance. Furthermore, the abundances of Na, Mg, and Al, relative to H, are all about 1 dex higher in HE 1327−2326 than in HE 0107−5240. Finally, an important difference is that two Sr lines are detected in the Subaru/HDS spectrum of HE 1327−2326, yielding [Sr/Fe] $= +1.2$ or $+0.9$, respectively, whereas no such lines are detected in the VLT/UVES spectrum of HE 0107−5240, yielding [Sr/Fe] $< -0.5$. The simultaneous absence of Ba in HE 1327−2326 results in a lower limit for the Sr/Ba ratio, i.e., [Sr/Ba] $> -0.6$. Therefore, the Sr seen in this star cannot have been produced by the main s-process. Other possible origins are the weak s-process or the r-process.

5.2.2. MODELS FOR THE ABUNDANCE PATTERNS One of the most important questions in the interpretation of the abundance patterns of these two stars is whether the gas clouds from which they formed had primordial composition, and only later the surfaces of these stars were polluted with metals (e.g., by dredged-up material from the interior of the star, mass transfer from a binary companion and/or accretion from the ISM), or if they had been pre-enriched by the yields of one or more supernovae. In the first case, HE 0107−5240 and HE 1327−2326 would be Population III stars. A number of models for the abundance pattern of HE 0107−5240 have been discussed in the literature. Here, we summarize these models and review their application to HE 1327−2326 (Frebel et al. 2005; W. Aoki, A. Frebel, N. Christlieb, J.E. Norris, T.C. Beers, et al., in preparation).

***Self-enrichment*** The large amounts of C, N, O, and Na exhibited in HE 0107−5240 could be due to self-pollution (Christlieb et al. 2002, 2004), as is predicted to occur in low-mass Population III stars following helium core flash in some models of stellar evolution (Fujimoto, Ikeda & Iben 2000; Siess, Livio & Lattanzio 2002). However, more recent calculations by Weiss et al. (2004) and Picardi et al. (2004) show that self-enrichment is unlikely, because the observed C/N and lower limits for the carbon isotopic ratio $^{12}C/^{13}C$ are both too high by about an order of magnitude. Furthermore, although the currently available constraints on the surface gravity are not yet very strong, it appears unlikely that HE 0107−5240 is in a post-helium core flash evolutionary state. For HE 1327−2326, self-enrichment is ruled out because it is an unevolved star close to the main-sequence turnoff (Frebel et al. 2005; W. Aoki, A. Frebel, N. Christlieb, J.E. Norris, T.C. Beers, et al., in preparation).

***Pollution from an AGB companion*** Suda et al. (2004) show that the surface abundance ratios of the elements up to Na of a Population III star with initial mass in the range 1.2–3 $M_\odot$ during its AGB phase match well with the abundance ratios observed in HE 0107−5240; similar calculations have been done for HE 1327−2326 (Suda et al., in preparation).

The former primary would today have evolved to a white dwarf and should be recognizable by radial velocity variations. This has not yet been observed for neither HE 0107−5240 (Bessell, Christlieb & Gustafsson 2004) nor HE 1327−2326 (Frebel et al. 2005; W. Aoki, A. Frebel, N. Christlieb, J.E. Norris, T.C. Beers, et al., in preparation), but membership in long-period and/or low-amplitude binary systems is not excluded for either of the stars. In fact, Suda et al. (2004) predict that HE 0107−5240 might have a period of the order of 150 years and orbital velocities of $\sim$7 km s$^{-1}$. Radial velocity monitoring of both stars is in progress.

***Pre-enrichment by supernovae*** Umeda & Nomoto (2003) proposed that the abundance pattern of HE 0107−5240 arises from material that has been enriched by a single 25 $M_\odot$ Population III star exploding as a supernova with an explosion energy of only $E_{\rm exp} = 3 \cdot 10^{50}$ erg. By assuming that the material produced during the SN event is homogeneously mixed over a wide range of the mass coordinate, and a large fraction of the material falls back onto the compact remnant, Umeda & Nomoto were able to reproduce the abundance pattern of HE 0107−5240 remarkably well (see their figure 1). Significant discrepancies exist between the observed and predicted abundances of oxygen (see Bessell, Christlieb & Gustafsson 2004) and sodium, but these can be removed by modifications of the model (Umeda & Nomoto 2005). "Faint SN" models have also been calculated by Iwamoto et al. (2005) to match the abundance pattern of HE 1327−2326, with similarly promising results.

Pre-enrichment of the gas cloud from which HE 0107−5240 formed by two SN II with masses of $\sim 35\ M_\odot$ and $\sim 15\ M_\odot$ has been discussed by Limongi, Chieffi & Bonifacio (2003) (see also Bonifacio, Limongi & Chieffi 2003). This model seems to be excluded on the basis of the high predicted oxygen abundance of [O/Fe] $= +4.1$ (see their Figure 3), which is in contradiction with the observed value of [O/Fe] $\sim +2.0$.

It seems also possible that the gas cloud has been pre-enriched by the yields of very massive SN ($M \sim 200\ M_\odot$; see Schneider et al. 2003). However, this could explain only the abundances of the elements heavier than Na, and for the lighter elements, other origins have to be sought.

***Pollution from the ISM*** The possibility that halo stars might have accreted heavy elements from a metal-rich ISM during their long lifetime was suggested and discussed, e.g., by Talbot & Newman (1977), Yoshii (1981), and Iben (1983). More recently, Shigeyama, Tsujimoto & Yoshii (2003) estimated that considerable accretion rates (on the order of $10^{-13}\ M_\odot\ \mathrm{yr}^{-1}$) can be reached if the velocity of the star relative to the gas cloud from which it accretes is low (i.e., ~10 km/s).

It thus appears possible that HE 0107−5240, and also HE 1327−2326 (Frebel et al. 2005; A. Frebel, N. Christlieb, J.E. Norris, T.C. Beers, et al., in preparation) have accreted amounts of heavy elements that lead to levels of [Fe/H] $\sim -5.5$. However, given that the convective zone of HE 0107−5240 is larger than that of HE 1327−2326, it would be expected that the heavy-element abundances of the former star should be significantly lower (because the accreted material was diluted into a larger mass of pristine gas), unless an additional depletion mechanism like diffusion has operated in HE 1327−2326 (Y. Yoshii 2004, private communication).

***Conclusions*** On the basis of the above scenarios, and the evidence available at present, it cannot yet be decided if HE 0107−5240 and HE 1327−2326 are second-generation stars that have formed from gas clouds that have been pre-enriched by the first generation of SNe, or if they are Population III stars that acquired the metals that we observe on their surfaces today only after their birth. We look for guidance from future observations of these and other yet-to-be-identified HMP stars, as well as from more detailed theoretical studies.

# 6. FUTURE WORK

## 6.1. What Remains to be Explored with Current Databases?

Medium-resolution spectroscopic follow-up of VMP candidates from the HK survey and the HES will continue for at least a few more years, given that several thousand stars remain to be observed. Furthermore, because of technical reasons, thus far only 329 out of the total of 380 HES fields have been searched for metal-poor candidates. The remaining 51 fields will be processed soon.

As noted above, spectroscopic follow-up of candidate metal-poor stars from the HK-II survey is presently underway. On the basis of the information obtained to date, the effective yield of VMP stars in HK-II is on the order of 40–50%, which is superior to the HK-I survey, and competitive with the HES. It is expected that follow-up of the most promising VMP candidates will be completed within the next several years.

Plans exist for obtaining snapshot spectra for all EMP and UMP stars discovered in the HK survey and the HES, with the aim of identifying, e.g., more r-II stars and additional stars with $[Fe/H] < -5.0$. For these stars, and at least all confirmed in this effort to have $[Fe/H] < -3.5$, we need to obtain high-resolution spectroscopy to study these objects in detail.

Exploitation of the full information contained in high-resolution spectra of VMP stars that have already been obtained (e.g., information about the scatter around the abundance trends) will require homogenous abundance analyses; that is, these spectra have to be analyzed using the same model atmospheres, line lists, atomic data for the lines used, adopted solar abundances, etc. Combination of abundances from the literature to a homogeneous set of values is very difficult, if not impossible, because individual analyses differ with respect to the issues listed above.

Beers (2005) has made the case for the establishment of an "elemental analysis clearinghouse," perhaps as part of the worldwide Virtual Observatory network, which would make it feasible for high-resolution spectroscopic data to be collected and analyzed (and periodically reanalyzed) in a uniform and homogeneous fashion. This effort would also open the wealth of abundance information that might be obtained by combining samples of stars, for use by nonspecialists and specialists alike.

It should also be noted that abundance trends may be affected by 3D and/or NLTE effects, which can have a strong [Fe/H] dependence (Asplund 2005, this volume). Therefore, 3D NLTE analyses should also be carried out, at the earliest opportunity, using the existing data for VMP stars.

## 6.2. What Requires Larger Databases?

There are a number of areas of importance that cannot (yet) be addressed with existing databases of MP stars. These include the following:

- *The nature of the metallicity distribution function (MDF) throughout the galactic halo*: Essentially all of the MP stars found in the HK survey and in the HES are located within ~20 kpc of the Sun. As a result, the MDF data that we have sufficient to explore in situ is only representative of the inner-halo population. Whether or not this MDF remains similar at larger distances provides important constraints on the formation history of the Milky Way. Furthermore, by better populating the VMP tail of the MDF (with 5–10 times the present numbers of stars), one can test whether the MDF is a continuous function, or if (as previous hints have suggested) it might contain structure that could be associated with bursts of star formation at various metallicities in the history of the Galaxy. Is there are real gap in the MDF between [Fe/H] $\sim -4.0$ and [Fe/H] $\sim -5.0$, and if so, what might account for its presence?

- *Existence of a lower limit to the MDF*: How low can we go? If low-mass stars were able to form at the very earliest times, there is the expectation that, with sufficient effort, ever larger databases can be constructed that should enable their detection in the halo today. The history of these searches provides a valuable lesson: With every large expansion of MP star samples, the low-metallicity "barrier" has moved significantly to lower abundances. Whether or not a physical barrier has been finally reached with the identification of the HMP stars can only be addressed with much larger samples.
- *The identification of "natural groups" of chemically similar stars*: Traditionally, elemental abundance ratios are presented in two-dimensional diagrams, e.g., [X/Fe] versus [Fe/H]; stars that lie significantly off the resulting trends are noted as chemically peculiar. However, the advent of large surveys, such as HERES survey, makes it feasible to examine the much richer "$N$-space" of elemental abundances, where $N$ comprises 15–20 species per star. With larger databases, one can readily find stars that share similar nucleosynthetic histories and seek to understand their origin in an astrophysical context. Sorting out the taxonomy of CEMP stars, as well as that of the s-process and r-process-rich metal-poor stars, is one clear example.

  The Karlsson & Gustafsson (2001) investigation is another example of such an approach, which has been elaborated further in Karlsson & Gustafsson (2005). In the latter work, they predict the presence of so-called single supernovae sequences (SSSs) in abundance ratio diagrams. Stars on SSSs formed from gas clouds that were enriched by single supernovae, and their abundances would hence allow one to empirically determine SN yields. However, the simulations of Karlsson & Gustafsson indicate that for the identification of such SSSs, abundance ratios with accuracies of the order of a few tenths of a dex need to be measured for several hundred stars.
- *The existence of kinematic streams*: Helmi et al. (1999), Chiba & Beers (2000), and Navarro et al. (2004) have searched the catalogs of radial velocities, proper motions, distances, and abundances of relatively nearby MP stars (e.g., Beers et al. 2000) in order to identify streams of stars that might be associated with a common parent, such as a ravaged dwarf galaxy. The technique employed is to compare the observed angular momentum distribution of program stars with models of the expected distributions obtained from random sampling of known stellar populations. This powerful approach identifies surviving structure in angular momentum space that cannot readily be found from spatial analysis alone. Larger samples will better populate

postulated streams and better constrain the "background" phase space from which they are identified.

## 6.3. Observational Challenges Presented by HMP Stars

HMP stars clearly provide an important tool for studying the first generation of stars and supernovae in the Universe, and currently we do not know for certain if these stars actually belong to the first generation of stars. It is therefore of utmost importance to find more examples of such stars. From the statistics of stars found so far, one can estimate that perhaps one to two additional stars at $[\mathrm{Fe/H}] < -5.0$ might be identified in the HES. New, deeper surveys are required to find even more of them, and such efforts are underway (see Section 6.4). However, even when blessed with additional HMP stars, we will continue to face difficult observational challenges.

The limitation arises because the absorption lines of elements other than hydrogen and, depending on effective temperature, of diatomic molecules involving C and N are extremely weak in HMP stars. For example, the two strongest Fe I lines detected in the Subaru/HDS spectrum of HE 1327−2326 have equivalent widths of only 5.9 mÅ and 6.8 mÅ, and several nights of observing time at the VLT/UT2 had to be invested to detect ultraviolet OH lines from which the oxygen abundance of HE 0107−5240 (Bessell, Christlieb & Gustafsson 2004) could be measured. A similar amount of time will be needed for HE 1327−2326, owing to its ~1000 K hotter effective temperature, which results in much weaker OH lines.

This demonstrates that, already for these relatively bright stars (note that the HES limiting magnitude is $B \sim 17.5$), we are approaching the limit of feasibility for conducting detailed abundance analyses of HMP stars. Many of the lowest metallicity stars to be found in new, deeper surveys can therefore perhaps only be studied in detail once the next generation of large ground-based telescopes is available, especially if it turns out that stars with metallicities even lower than that of HE 0107−5240 and HE 1327−2326, i.e., MMP stars, exist in the Galaxy.

## 6.4. Future Surveys

In this section we discuss new surveys capable of finding significant numbers of additional VMP stars. We restrict ourselves to projects that have already started or are funded.

6.4.1. **RAVE** The RAdial Velocity Experiment (RAVE)[3] aims at obtaining $R = 10{,}000$ spectra of some 50 million stars in the Northern and Southern Hemispheres (Steinmetz et al. 2002). The spectral resolution and wavelength range (8400–8750 Å) is chosen to match that of the Radial Velocity Spectrometer (RVS) planned for the Gaia satellite (see Section 6.4.5). At $S/N = 20/1$ for a $V = 16$ mag star,

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[3] See http://www.aip.de/RAVE/

it is expected that radial velocities can be measured with an accuracy of 1 km s$^{-1}$ and that at least [Fe/H] and [$\alpha$/Fe] can be determined for most of the targets.

Currently, a pilot study aiming at the observation of some 100,000 stars is being carried out using the 6dF facility at the 1.2 m UK Schmidt telescope, which enables one to observe up to 150 objects simultaneously in a 6° diameter field-of-view. A 1200 grooves mm$^{-1}$ VPH grating is used, yielding $R = 4000$. For the main project, the 6dF robotic fiber positioner is planned to be replaced by UKidna, a fiber positioning device based on ball spines. The use of 2250 spines per field and configuration times as short as 5 min will make it feasible to observe some 5 million stars per year at each of the two telescopes to be used (one in each hemisphere).[4] It is planned to reach a completeness limit of $V = 16$.

Apart from providing unprecedented information on the structure and kinematics of all of the stellar components of the Galaxy, RAVE has the potential of identifying significant numbers of new VMP stars, in particular in those areas of the sky that are not covered by either the HK survey or the HES.

6.4.2. THE SIDING SPRING/HAMBURG SURVEY The Siding Spring/Hamburg Survey (SSHS) is a new slitless survey for metal-poor stars in the Southern Hemisphere. The soon-to-be fully robotic Siding Spring Observatory 1 m telescope, equipped with an 8 k × 8 K CCD Wide Field Imager (field of view 52 × 52 arcmin), will be used for obtaining spectra with a seeing-limited spectral resolution comparable to that of the HES, i.e., ~10 Å at Ca II K. To increase the survey volume for metal-poor stars, the survey will be slightly deeper than the HES (i.e., $B \sim 18$) and will concentrate (initially) on areas of the sky not covered by the HES.

6.4.3. SDSS AND SEGUE At the time of this writing, medium-resolution ($R = 1800$) spectroscopic data obtained during the course of the SDSS now exist in the public domain for on the order of 75,000 galactic stars.[5] Analysis pipelines have been developed, and value-added catalogs that summarize best estimates of atmospheric parameters ($T_{\mathrm{eff}}$, log $g$, [Fe/H]), as well as radial velocities, distance estimates, and proper motions, are now being assembled (T.C. Beers, C. Allende Prieto, R. Wilhelm, B. Yanny, C. Rockosi, et al., in preparation). By the time the main SDSS survey is completed, the number of stars with similar data available will be on the order of 100,000. Although they were not specifically targeted as metal-poor candidates, this database contains large numbers of VMP and EMP stars, as well as many CEMP stars. On the basis of analysis carried out to date, the public SDSS database should eventually contain on the order of 5000–10,000 VMP stars, and perhaps 500–1000 EMP stars.

Plans are presently being made, and tests of target selection and analysis techniques are being completed, for another great expansion of our observational

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[4] According to Steinmetz et al. (2002) the Northern Hemisphere telescope has not yet been identified. Candidates are the Japanese Kiso Schmidt telescope and the Chinese LAMOST.

[5] See http://www.sdss.org/

database of interesting stars in the Galaxy. This survey effort, known as SEGUE, Sloan Extension for Galactic Understanding and Exploration, will, as the acronym suggests, be employing the same telescope (the ARC 2.5 m telescope on Apache Point, New Mexico), imager, spectrographs, and reduction pipeline as the original SDSS to dramatically enhance our knowledge of the stellar populations of the Milky Way. SEGUE, presently scheduled to start in July 2005 and finish by July 2008, will obtain some 3000 square degrees of calibrated *ugriz* photometry at lower galactic latitudes than the SDSS main survey, so as to better constrain the important transition from the disk population(s) to the halo. Most importantly, SEGUE will obtain medium-resolution spectroscopy for 250,000 stars in the magnitude range $13.5 \leq g \leq 20.5$, in 200 directions covering the sky available from Apache Point. SEGUE targets have been chosen to explore the Galaxy at distances from 0.5 to 100 kpc from the Sun.

One of the primary SEGUE categories is obtained from photometric preselection of likely VMP stars. Tests carried out to date indicate that it is reasonable to expect that SEGUE will yield a sample of at least 25,000 VMP stars, a factor of 10 times the present number of such stars known from the summed efforts of astronomers to date. Although the majority of these VMP stars will be too faint for easy high-resolution spectroscopic follow-up with 8–10 m telescopes (but tractable with 30–100 m ones!), there will be at least several thousand that are sufficiently bright. Plans are presently being made to undertake HERES-like snapshot spectroscopy with the Hobby-Eberly, Subaru, and (perhaps) the Keck telescopes, followed by higher $S/N$ studies of the most interesting objects that are revealed.

6.4.4. LAMOST The Chinese Large sky Area Multi-Object fiber Spectroscopic Telescope (LAMOST)[6] is planned to be a 4 m telescope capable of simultaneously observing 4000 objects in an area of $5^\circ \times 5^\circ$ of the Northern Hemisphere sky. With 16 two-arm spectrographs, spectra of $R = 1000$–$3000$ covering 370–620 nm and 600–900 nm can be obtained (G. Zhao 2004, private communication). Performance estimates indicate that, at the lowest spectral resolution, $S/N = 10$ can be reached for a $V = 20$ mag object in a few hours. The time for re-configuring the fibers is expected to be on the order of half an hour, so that many fields per night can be observed. LAMOST first light is planned for mid-2006.

The combination of a large aperture and field of view with high multiplexity and resolving power makes LAMOST an ideal facility for conducting searches for the most metal-poor stars. The spectra used for vetting metal-poor candidates found in previous wide-angle spectroscopic surveys like the HK survey and the HES typically have $R = 2000$ and $S/N = 20/1$. Provided that spectra of similar quality will be obtained with LAMOST, it is expected that the success rate for identifying bona fide EMP stars with $[\mathrm{Fe/H}] < -3.0$ will be close to 100%.

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[6] http://www.lamost.org/

6.4.5. GAIA Gaia[7] is an astrometric satellite that, according to current plans, will be launched by ESA in mid-2011 (Perryman et al. 2001). Over a mission duration of 5 years, Gaia will conduct a magnitude-limited full-sky survey down to $V = 20$. In addition to astrometry with an accuracy of 10 $\mu$as at $V = 15$, it will obtain $R = 11{,}500$ spectroscopy in a region covering the Ca infrared triplet (8480–8740 Å) and conduct photometric observations in a medium-band system consisting of 14 filters and a broad-band system of 5 filters.[8] Simulations indicate that it will be feasible to reliably identify VMP stars in the Gaia database of $\sim 10^9$ objects. However, from the considerations mentioned in Section 3.2, it is clear that complementary ground-based follow-up observations will be needed to identify the most metal-poor stars observed with Gaia.

A successful Gaia mission will revolutionize our understanding of the formation, structure, and chemical evolution of the Galaxy.

6.5. FINAL THOUGHTS The search for, and the analysis of, the most metal-deficient stars in the Galaxy has progressed from doubts of their very existence to reliance upon them for insight into the nature of the first stars, the early Galaxy, and the Universe. In the next few decades we expect that these probes of the formation of the first stars, and the elements they produced, will continue to push observers and theoreticians to explain the wide variety of phenomena that they exhibit. The excitement of discovery has only begun.

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[7] http://astro.estec.esa.nl/GAIA/

[8] See reports UB-PWG-028 and UB-PWG-029 on the Web page of the Gaia Photometry Working Group, http://gaia.am.ub.es/PWG/index.html.

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