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Extremely Metal-poor Stars

JOHN E. NORRIS
Research School of Astronomy & Astrophysics, The Australian National University

Abstract

The discovery and analysis of extremely metal-poor stars have led to increasing insight into conditions when the Universe and Galaxy were young. We present the rationale for studying such objects, with a description of their systematic discovery, culminating in the recent analysis of an object having [Fe/H] = –5.3. We discuss the abundance patterns of several elements from Li through to the heavy neutron capture elements. Relatively few extremely metal-poor stars with [Fe/H] $<$ –3.5 have been analyzed at high spectral resolution and high signal-to-noise ratio, but some 40% of that sample show astounding overabundances of some or all of the CNO group and the lighter α elements. At [Fe/H] $\approx$ –3.0, some stars show enormous enhancements of *r*-process elements, leading to age determinations. The diversity among the most metal-poor stars has yet to be fully understood.

1.1 Introduction

Extremely metal-poor stars provide fundamental clues to conditions at the earliest times. In the half century since the pioneering high-resolution chemical abundance analysis of spectra of metal-poor objects obtained using Carnegie's Mount Wilson 100-inch telescope by Chamberlain & Aller (1951), the field has continued to grow and is still attracting large allocations of observing time on the largest reflectors.

The rationale for the continued interest in these objects may be summarized as follows:

- They are the stars closest in time to the Big Bang.
- The abundance of lithium in metal-poor main sequence stars places constraints on Big Bang nucleosynthesis and the density of baryonic material in the Universe.
- Having formed at redshifts $z \gtrsim 4-5$, they probe conditions when the first heavy element-producing objects formed.
- They constrain our understanding of the explosions of the first supernovae/hypernovae.
- They provide clues on the manner in which the ejecta of the first supernovae were incorporated into later generations.
- They provide insight into the initial mass function at earliest times.
- They constrain our understanding of the manner in which the Galaxy formed.
- In some objects with large relative overabundances of the heavy neutron capture elements, the measurement of the abundances of thorium and uranium permits estimates of stellar ages, and hence that of the Galaxy.

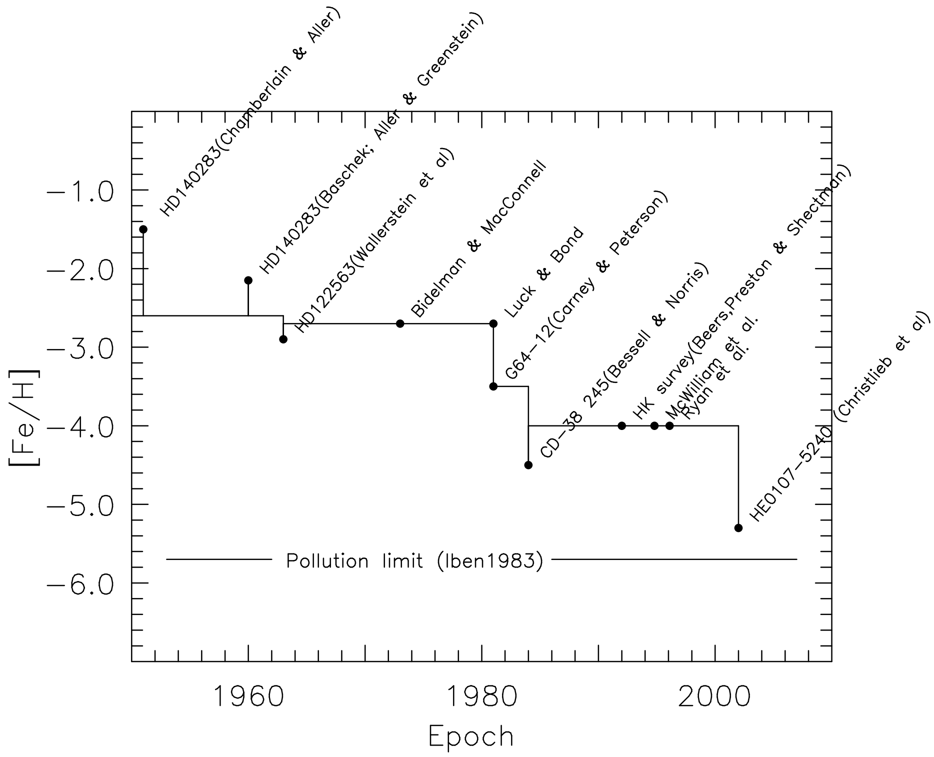

Fig. 1.1. [Fe/H] for the most metal-poor star then known as a function of epoch. The symbols refer to the values published by the authors, and are connected to currently accepted values (with the exception of HE 0107–5240).

1.2 Discovery

Chamberlain & Aller (1951) first explained the anomalous spectra of high-velocity stars in terms of lower chemical abundances. Sandage (1986) describes their work as "unbelievably revolutionary," providing as it did one of the fundamental parameters of stellar populations, at a time when the prevailing wisdom was that all stars had the same chemical properties. (He also nicely relates "a widely circulated underground story*" in which "It is asserted that the authors had first obtained heavy element abundance deficiencies of $\sim$100 relative to the Sun (in fact, the modern value), but this seemed so outrageous that the authors themselves ... changed the atmospheric temperatures sufficiently to reduce the effect from a factor of 100 to a factor of $\sim$10–30, the value they ultimately published."

Figure 1.1 shows the steady downward march with time of the iron abundance of the most metal-poor object then known. The record is currently held by HE 0107–5240 (Christlieb et al. 2002) with [Fe/H] = –5.3. Also shown in the figure is the estimate by Iben (1983) of the abundance one would measure for a hypothetical red giant that formed at the earliest times from material containing no heavy elements, and which accreted material from the ambient interstellar medium as it orbited the Galaxy until the present epoch.

Extremely metal-poor stars are rare. In the solar neighborhood $\sim$one in 1000 stars belongs

* C. Sneden notes: "I personally heard this story from Chamberlain himself, so I think it is pretty accurate."

to the metal-poor halo population to which such objects belong. Further, simple models of chemical enrichment of a primordial cloud predict that at lowest abundance the number of metal-poor objects decreases by a factor of 10 for each factor of 10 decrease in metal abundance. Roughly speaking, then, one might expect some five in a million stars to have [Fe/H] $<$ –3.5.

The discovery of extremely metal-poor objects has been a painstaking process, and has proceeded, essentially, in three ways:

(1) *Informed serendipity.* Two cases will illustrate the point. Attention was first drawn to the extremely metal-poor red giant CD–38°245 ([Fe/H] = –4.0) by Slettebak & Brundage (1971) in their search for A stars at the South Galactic Pole. The carbon-rich binary dwarf G77–61 ([Fe/H] = –5.5) was first extensively investigated astrometrically. It was only in subsequent studies that their extreme metal deficiency was appreciated (Bessell 1977; Gass, Wehrse, & Liebert 1988). (It would also seem reasonable to note that the extreme value claimed for G77–61 by Gass et al. requires confirmation.)

(2) *Systematic surveys of high-proper motion stars.* The low-resolution spectroscopic surveys of the high-proper motion catalogs of Giclas and Luyten, which selectively sample the halo population kinematically, provided the first estimates of the fraction of halo material having [Fe/H] $<$ –3.0. See Ryan & Norris (1991) and Carney et al. (1994).

(3) *Systematic objective prism surveys for weak-lined objects with Schmidt telescopes.* Following the early work of Bidelman & MacConnell (1973), Schmidt telescopes have become the predominant source of extremely metal-poor candidates. Using follow-up intermediate-resolution spectroscopy of the Ca II K line (as proxy for the heavy elements), the HK surveys of Beers, Preston, & Shectman (1985, 1992) and Beers and co-workers (see Beers 1999), together with the HES survey of Christlieb and collaborators (see Christlieb at al. 1999) are now producing statistically significant numbers of such objects. At time of writing, these authors are discovering a few tens of objects (based on intermediate-resolution spectra ($R \approx 2000$) with [Fe/H] $<$ –3.5 (Beers and Christlieb, private communications).

While the list of extremely metal-poor stars is growing rapidly, only a handful have published abundance analyses based on high-resolution ($R \approx 50,000$), high signal-to-noise ratio (S/N $\approx$ 100) spectra. (That said, see Spite et al. 2004 for an early report on data obtained with the VLT/UVES combination.) Table 1.1 presents the eight (and possibly nine) objects having [Fe/H] $\lesssim$ –3.5 for which high-quality data are available (from Gass et al. 1988; Norris, Beers, & Ryan 2000; Norris, Ryan, & Beers 2001; Aoki et al. 2002a; Christlieb et al. 2002). Note that six of the nine were discovered in the HK and HES surveys.

1.3 The Halo Metallicity Distribution Function

Figure 1.2 presents the metallicity distribution function for several halo samples. The rarity of the most metal-poor objects is clear in the figure: currently only 2–3 objects are known with [Fe/H] $<$ –4.0. The data in the lower panels are still preliminary, but they rule out the simple model of Galactic chemical enrichment of a zero heavy element abundance system (Searle & Sargent 1972; Hartwick 1976; Ryan & Norris 1991)—the predicted number decrease by a factor of 10 per factor of 10 decrease in abundance is not seen. The data provide the starting point for more complicated models, such as those of Tsujimoto, Shigeyama, & Yoshii 1999); see also Oey (2004).

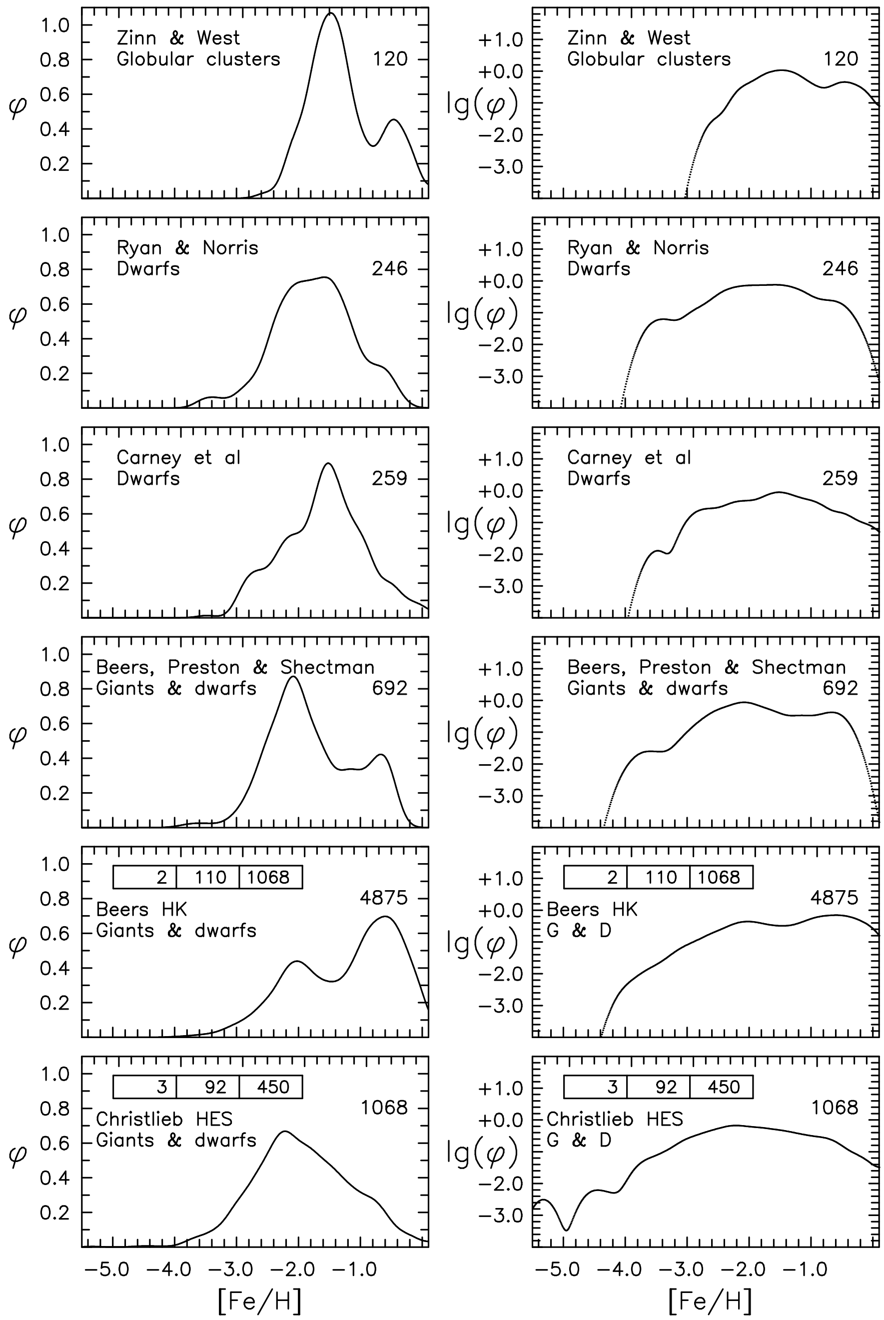

Fig. 1.2. The metallicity distribution function for several halo samples: globular clusters (Zinn & West 1984), high-proper motion objects (Ryan & Norris 1991; Carney et al. 1994), and Schmidt surveys (Beers et al. 1992; Beers 1999; Christlieb 2002, private communication). The data are presented as generalized histograms with Gaussian kernel having σ = 0.15. In each panel the total sample size is given on the right, while in the bottom two sets of panels the numbers in the boxes contain the sample size per abundance decade.

Table 1.1. *Stars with [Fe/H] $\lesssim$ –3.5 and Comprehensive Abundance Analysis*

Object	[Fe/H]	Technique	Type
CD–38°245	–4.0	Serendipity	Giant
CD–24°17504	–3.4	High proper motion	Dwarf
CS 22876–032	–3.7	Schmidt BPS	Dwarf
CS 22885–096	–3.7	Schmidt BPS	Giant
CS 22949–037	–3.8	Schmidt BPS	Giant
CS 22172–002	–3.6	Schmidt HK	Giant
CS 29498–043	–3.7	Schmidt HK	Giant
HE 0107–5240	–5.3	Schmidt HES	Giant
& possibly			
G 77–61	–5.5	Serendipity	Dwarf

1.4 Lithium

Spite & Spite (1982) first demonstrated that halo main sequence stars hotter than $T_{\rm eff} \approx 5500$ K appear to have the same lithium abundance—A(Li) = log N(Li)/N(H) + 12.0 $\approx$ 2.0. Subsequently, enormous effort has been expended to interpret this in terms of the primordial lithium abundance, and via Big Bang nucleosynthesis to determine the baryonic density of the Universe. To achieve the transition, one has to understand Li production and destruction mechanisms since the Big Bang. While this lies outside the scope of the present review, suffice it to say that one has to determine the amount of Li created by spallation in the interstellar medium and destroyed in and/or removed from the outer layers of main sequence halo stars by processes such as diffusion and rotational mixing.

There have been claims that A(Li) increases with increasing [Fe/H] at lowest abundance (Norris, Ryan, & Stringfellow 1994; Thorburn 1994; Ryan, Norris, & Beers 1999)—and counterclaims (Molaro, Primas, & Bonifacio 1995). Figure 1.3 shows data for an unbiased sample of field stars from Ryan et al. (1999), supporting the case that a positive correlation exists. The first reason for presenting this diagram is to emphasize the role of extremely metal-poor stars: the reader will need little convincing that further objects having [Fe/H] < –3.5 are needed to more strongly constrain the result.

A second point to take from Figure 1.3 is that there is little dispersion in A(Li). Ryan et al. (1999) claim that the dispersion is so small that it "limits permissible depletion by rotationally induced mixing models to less than 0.1 dex." For a counterargument, that the data permit a 0.2 dex median depletion, the reader should see Pinsonneault et al. (2002). (For recent, conflicting, claims on the Li abundance spread in near main sequence turn-off stars in globular clusters, see Bonifacio et al. 2002 and Boesgaard 2004.)

One should be alive to the fact that the Li abundances cited above are determined by using one-dimensional (1-D) model atmospheres and the assumption of local thermodynamic equilibrium (LTE). Asplund et al. (1999) and Aspund, Carlsson, & Botnen (2003) show that for models of near main sequence turn-off stars having [Fe/H] = –2.5, a change to 3-D decreases A(Li) by $\sim$0.3, while non-LTE modeling leads to an increase by a similar amount, and thus a net error of order only 0.05. It will be interesting to learn whether the cancellation applies for [Fe/H] = –4.0.

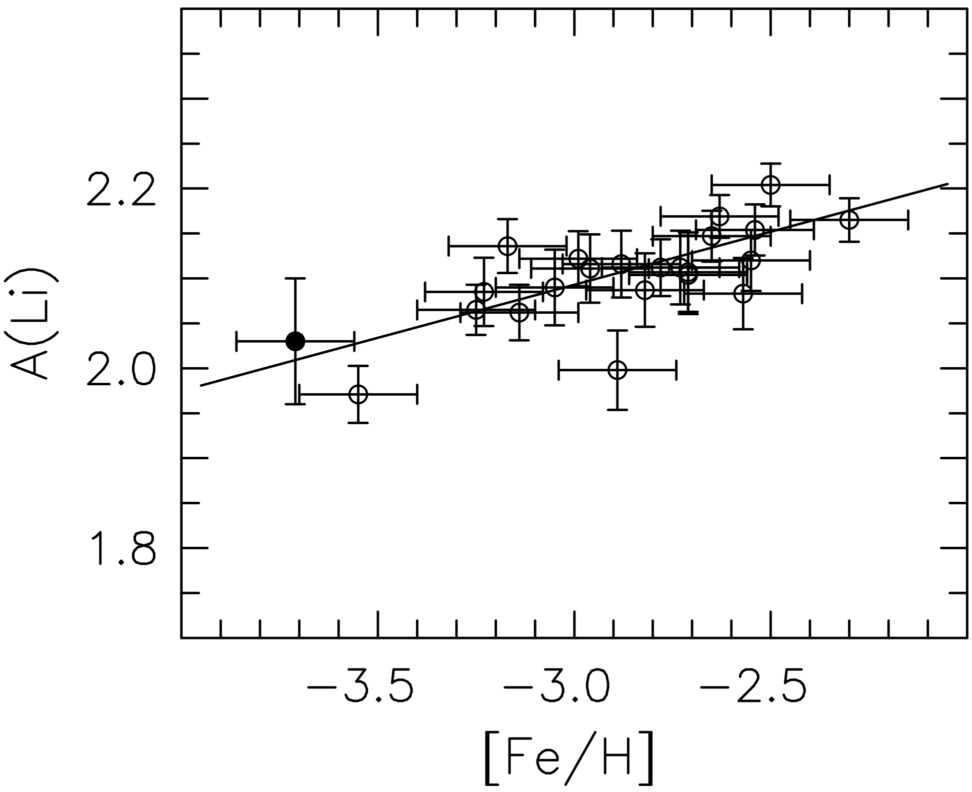

Fig. 1.3. A(Li) versus [Fe/H], from Ryan et al. (1999) and Norris et al. (2000).

Depending on one's view of the implications of abundance spread on the Spite Plateau for Li depletion, the dependence of A(Li) on [Fe/H], and model atmosphere assumptions, one comes to different values of the primordial lithium abundance. Ryan et al. (2000), for example, report $\mathrm{Li}_p = 1.23^{+0.68}_{-0.32} \times 10^{-10}$, leading to $\Omega_b h^2 = 0.006$–0.014. This is lower than the value of $\Omega_b h^2 = 0.021 \pm 0.002$ reported by O'Meara et al. (2001) from primordial deuterium measurements, and the Spergel et al. (2003) value of $\Omega_b h^2 = 0.022 \pm 0.001$ from the *WMAP* experiment.

If one turns the argument around, and adopts the *WMAP* result and the Big Bang nucleosynthesis Li abundance ($\mathrm{Li}_p \approx 4 \times 10^{-10}$) as given, one now has the option to use the Li observations to constrain production and destruction mechanisms, and the accuracy of the model atmosphere abundance analysis.

1.5 Relative Abundances versus [Fe/H]

Relative abundances, [M/Fe], contain important clues to the nature of the first heavy element-producing objects. In what follows, emphasis is given to the most metal-poor stars—those having [Fe/H] $<$ –3.5—and what they have to tell us about these objects.

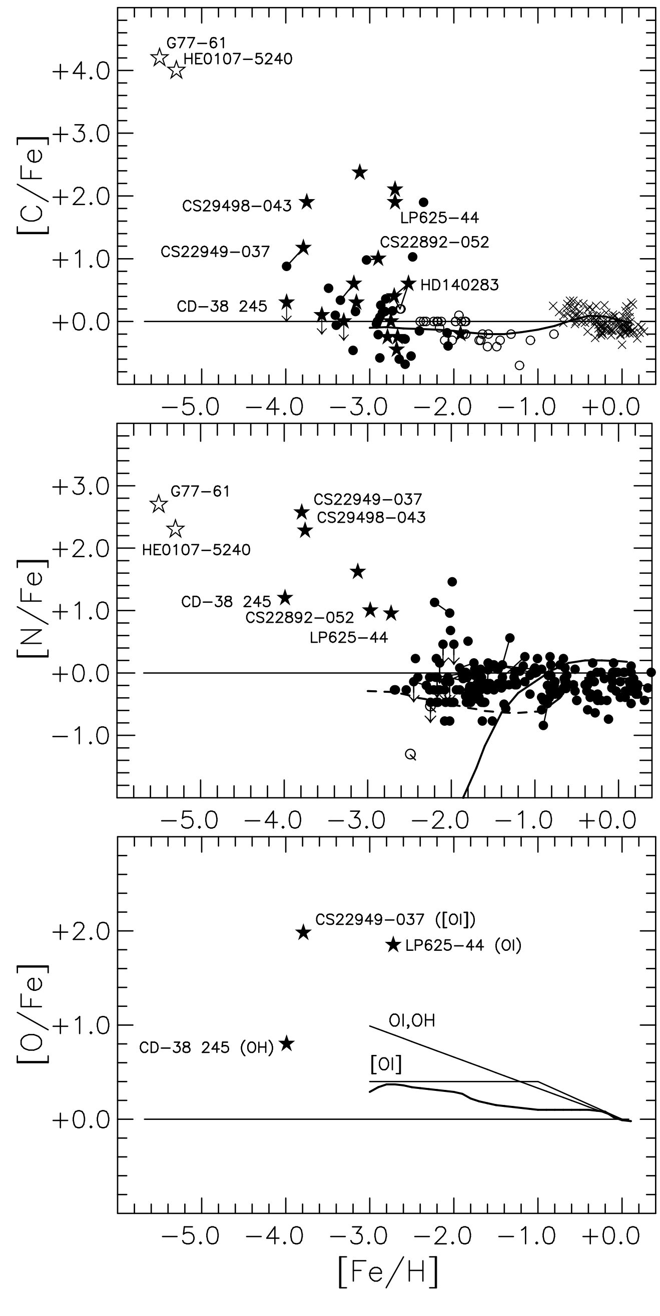

Fig. 1.4. Relative C, N, and O abundances. The sources of the data are given in Norris, Ryan, & Beers (1977), Norris (1999), and in the text. For oxygen, schematic representations are shown of recent results based on [O I] λ6300 Å, on the one hand, and the O I infrared triplet and ultraviolet OH lines, on the other. The full lines are from the theoretical models of Timmes, Woosley, & Weaver (1995), while the dashed line in the middle panel represents their result with the arbitrary inclusion of convective overshoot.

1.5.1 CNO

At the lowest values of [Fe/H], the results for the CNO group are astounding and totally unexpected, as demonstrated in Figure 1.4. Of the eight stars (excluding G77–61)* in Table 1.1, which have [Fe/H] $<$ –3.5 (and which form an unbiased sample as far as CNO abundances are concerned), three have [C/Fe] $>$ +1.0 and [N/Fe] $>$ +2.0, while a fourth has [N/Fe] = +1.2. One of the three (CS 22949–037) has [O/Fe] = 2.0†. (For details, see Norris et al. 2001, 2002; Aoki et al. 2002a; Christlieb at al. 2002; Depagne et al. 2002).

We defer discussion of these results to § 1.6.2.

1.5.2 α Elements

Results for the α elements are shown in Figure 1.5, and are as presented by Norris et al. (2001), with additional material from Aoki et al. (2002a, CS 29498–043) and Christlieb et al. (2002, HE 0107–5240).

Of the eight extremely metal-poor stars in Table 1.1, CS 22949–037 and CS 29498–043 have [Mg/Fe] $>$ 1.0. The overabundances for these objects are real and outside uncertainties in the analysis. Errors are large for [Si/Fe], but here, too, these objects appear to have [Si/Fe] $>$ 1.0. They also have large enhancements of C, N, and O, which sets them apart from the remainder of the group. We shall return to these objects in § 1.6.2.

1.5.3 Iron-peak Elements

For data on the relative abundances for the iron-peak elements the reader is referred to McWilliam et al. (1995), Ryan et al. (1996), and Norris et al. (2001). Of particular importance is the result that for [Fe/H] $\lesssim$ –3.0, [Cr/Fe] and [Mn/Fe] decrease as [Fe/H] decreases, while [Co/Fe] increases. [Ni/Fe] maintains its solar value. These results were not predicted by supernova modeling, but Nakamura et al. (1999) and Umeda & Nomoto (2002) have investigated the effects in terms of the assumed mass cut for the ejection of material in supernova explosions, and the energy of explosion. The reader is referred to Umeda & Nomoto for their explanation of the observations in terms of the explosion of hypernovae with energies of 50 $\times$ 10^{51} erg. The discussion presents a nice example of the interplay between observation and theory.

1.5.4 Heavy Neutron Capture Elements

Results for the heavy neutron capture elements Sr and Ba are shown in Figure 1.6. The enormous spread in [Sr/Fe] of 2 dex at [Fe/H] $\approx$ –3.5 attests to the patchy nature of the enrichment of these elements. [Ba/Fe], on the other hand, does not show the same range, which suggests that more than one type of object is responsible for the enrichment of these elements. The reader is referred to McWilliam (1998), Blake et al. (2001), and Ryan et al. (2001) who discuss this in terms of the basic *r*-process necessary to explain the well-established patterns of abundance in stars with [Fe/H] $<$ –2.5, and an ill-defined second one that favors production of elements of heavy neutron capture elements of lower atomic number.

Further evidence for patchy enrichment comes from [Eu/Fe] versus [Fe/H], as is summarized by Truran et al. (2002), down to [Fe/H] = –3.0. Fields, Truran, & Cowan (2002)

* While it is probably not unreasonable to say that most astronomers with an interest in the matter are reserving judgement on the reality of [Fe/H] = –5.5 for G77–61, given the similarity of its carbon and nitrogen abundances to those of some of the other stars with [Fe/H] $<$ –3.5, confirmation of its iron abundance takes on a new light.

† It is worth noting that Israelian (2004) reports [O/Fe] = 3.2 in CS 29498–043.

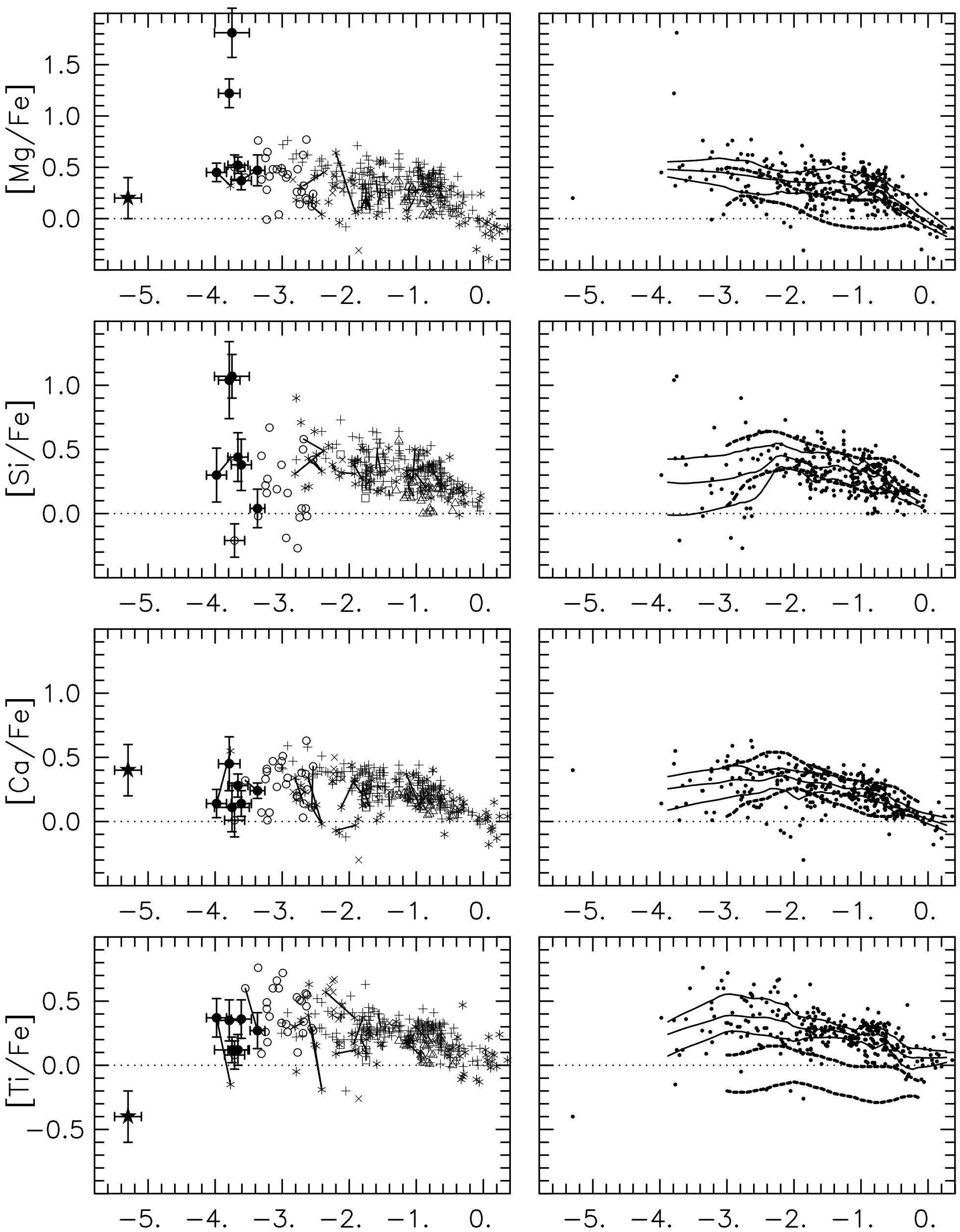

Fig. 1.5. Relative abundances for the α elements as a function of [Fe/H]. The data are as presented by Norris et al. (2001), with the addition of CS 29498–043 and HE 0107–5240 from Aoki et al. (2002a) and Christlieb et al. (2002), respectively. In the right panel, the thin lines (effectively) represent running means and quartiles, while the thicker lines are theoretical results from Timmes et al. (1995).

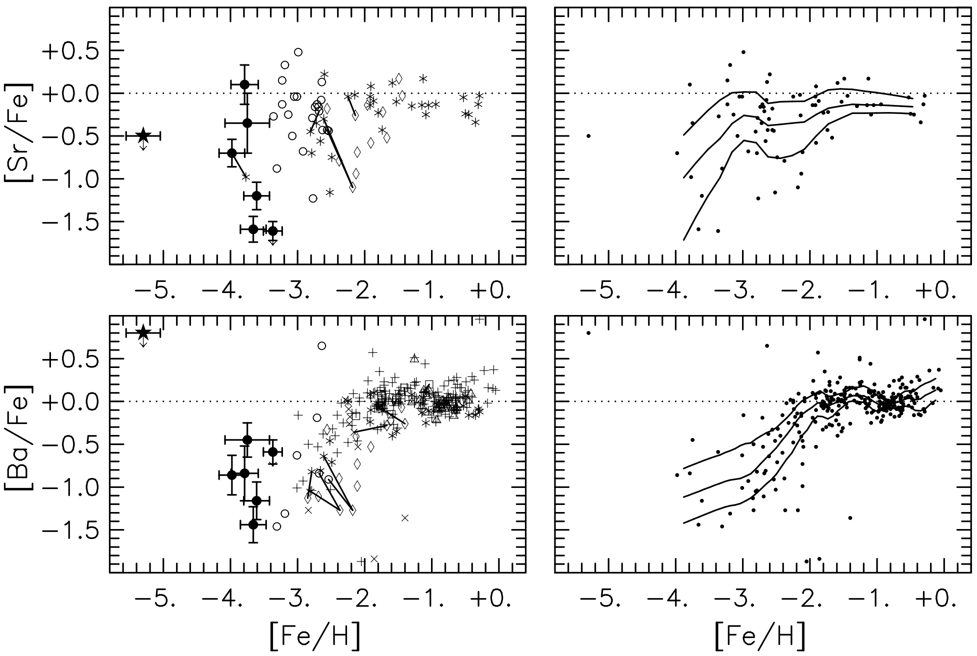

Fig. 1.6. [Sr/Fe] and [Ba/Fe] versus [Fe/H], from Norris et al. (2001), together with data from Aoki et al. (2002a, CS 29498–043) and Christlieb et al. (2002, HE 0107–5240). In the right panel the lines (effectively) represent running means and quartiles.

describe the results in terms of the different frequency of supernovae that produce *r*-process elements and iron. They note that data for [Fe/H] < –3.0 will be able to distinguish various possibilities. Given the intrinsic weakness of the europium lines available for measurement, however, this will not be a trivial task.

1.6 Abundance as a Function of Atomic Number

1.6.1 Stars with Extreme Enhancements of r- and s-Process Elements

One of the most exciting results to emerge from the study of extremely metal-poor stars has been the discovery of objects with [Fe/H] ≈ –3.0 with enormous overabundances of the heavy neutron capture elements in an *r*-process pattern—in particular CS 22892–052 (see Sneden et al. 1996, 2003) and CS 31082–001 (Cayrel et al. 2001). Figure 1.7 shows [M/H] versus atomic species for these stars, together with comparison data for the "normal" metal-poor red giant HD 122563. Also shown are results for LP 625–44, which exhibits huge *s*-process enhancement rather than the *r*-process pattern. (This can be seen from the overabundance of Ba relative to Eu in LP 625–44 in contrast to its relative underabundance in CS 22892–052 and CS 31082–001.)

Stars such as LP 625–44 are normally assumed to result from mass transfer of material from an asymptotic giant branch star across a binary onto the companion star that is now observed—giving insight into asymptotic giant branch nucleosynthesis at very low abundance (see Aoki et al. 2002b). It is not clear, however, that this provides a complete explana-

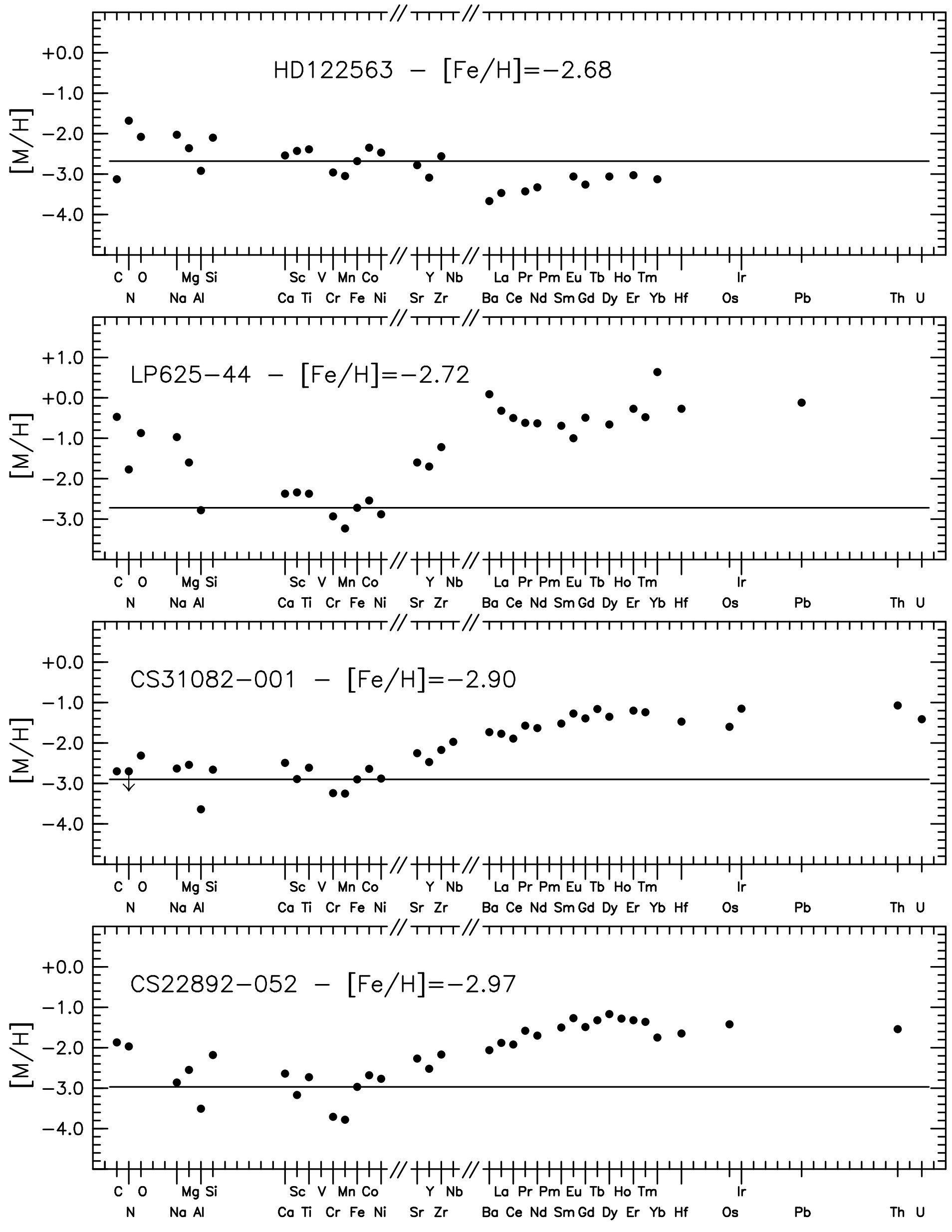

Fig. 1.7. Abundance relative to hydrogen for HD 122563 and the heavy neutron capture element-enhanced stars LP 625–44, CS 31082–001, and CS 22892–052. (Data from Lambert, Sneden, & Ries 1974; Sneden & Parthasarathy 1983; McWilliam et al. 1995; Ryan et al. 1996; Sneden et al. 1996; Norris et al. 1997, 2001; Aoki et al. 2002b; Hill et al. 2002.)

tion of all metal-poor stars with *s*-process enhancement. Witness [O/Fe] = 1.8 in LP 625–44 (Aoki et al. 2002b), which is difficult to explain in this manner, and the apparent radial velocity constancy of the strongly s-process-enhanced, metal-poor ([Fe/H] = –2.7) star LP 706–7 (Norris et al. 1997).

The reader is referred to Truran et al. (2002), Cayrel et al. (2004), and references therein, for details of age determinations based on Th and U abundances for the some half dozen r-process-enhanced objects currently known—which fall in the range 11–15 Gyr. The work of Wanajo et al. (2002) is also of considerable interest. They note that ages determined in this manner are very sensitive to the currently somewhat poorly understood modeling of the objects responsible for the r-process enhancements.

There is one final point from Figure 1.7 worth comment. In spite of the general similarity between the abundance patterns of CS 22892–052 and CS 31082–001, the behavior of C and N is quite different. In the latter, [C/Fe] has the solar value, while in the former [C/Fe] and [N/Fe] are overabundant by 1 dex. Canonical wisdom assumes that two processes have operated in CS 22892–052, and only one in CS 31082–001, but offers little insight into the matter. There is, however, suggestive but weak evidence that CS 22892–052 may be a binary (Preston & Sneden 2001).

1.6.2 Stars with Extreme CNO and Mg Enhancements

As noted in § 1.5.1, three of the most metal-poor stars (HE 0107–5240, CS 22949–037, and CS 29498–043) have enormous overabundances of some or all of C, N, and O, and the light α elements. Figure 1.8 compares their abundances, as a function of atomic species, with those of the "normal" extremely metal-poor star CD–38°245. The important point to note here is that the anomalously high abundances in the CNO-enhanced objects pertain only to elements less massive than Ca. The iron-peak and heavy neutron capture elements do not appear abnormal.

This behavior has led to suggestions that the peculiar abundance patterns seen in CS 22949–037 and CS 29498–043 are the result of ejecta from a supernova that has expelled only its outermost parts, with the iron-peak-enriched material falling back onto the exploding object (McWilliam et al. 1995; Norris et al. 2001, 2002; Depagne et al. 2002; Umeda & Nomoto 2003). The reader is referred to the paper by Nomoto (2004) in this volume. In the case of CS 22949–037, Umeda & Nomoto postulate a "mixing and fallback" model in which a 30 $M_\odot$ supernova, exploding with energy 20 $\times$ 10^{51} erg, completely mixes material within its 2.33–8.56 $M_\odot$ mass shell, with most of the shell falling back onto the star and only a small fraction (f = 0.002) being expelled. The model produces a good fit to the data except for N, where it fails completely, and also for Na.* In the case of N a further process is required, postulated to be subsequent CN cycle burning and mixing into the envelope of the star currently being observed. Nitrogen enhancements are common in globular cluster giants, but not in the field, and have been suggested to originate in this manner.

The nitrogen problem is an outstanding one. Inspection of the middle panel of Figure 1.4 suggests that canonical models fail to explain the apparently primary nature of nitrogen observed down to [Fe/H] = –2.5, and solutions such as rotation, convective overshoot, and the massive zero-heavy element hypernovae (massive pair instability supernovae) of Woosley & Weaver (1982) have been advocated (see Norris et al. 2002, and references therein).

* Umeda & Nomoto (2003) explain the abundance pattern of HE 0107–5240 in terms of a "mixing and fallback" model of a supernova of mass 25 $M_\odot$, explosion energy 0.3 $\times$ 10^{51} erg, mixing within a shell of 1.83–6.00 $M_\odot$, and an expelled mass fraction f = 0.00002. Note the large factor (60) between the explosion energies of the models for CS 22949–037 and HE 0107–5240.

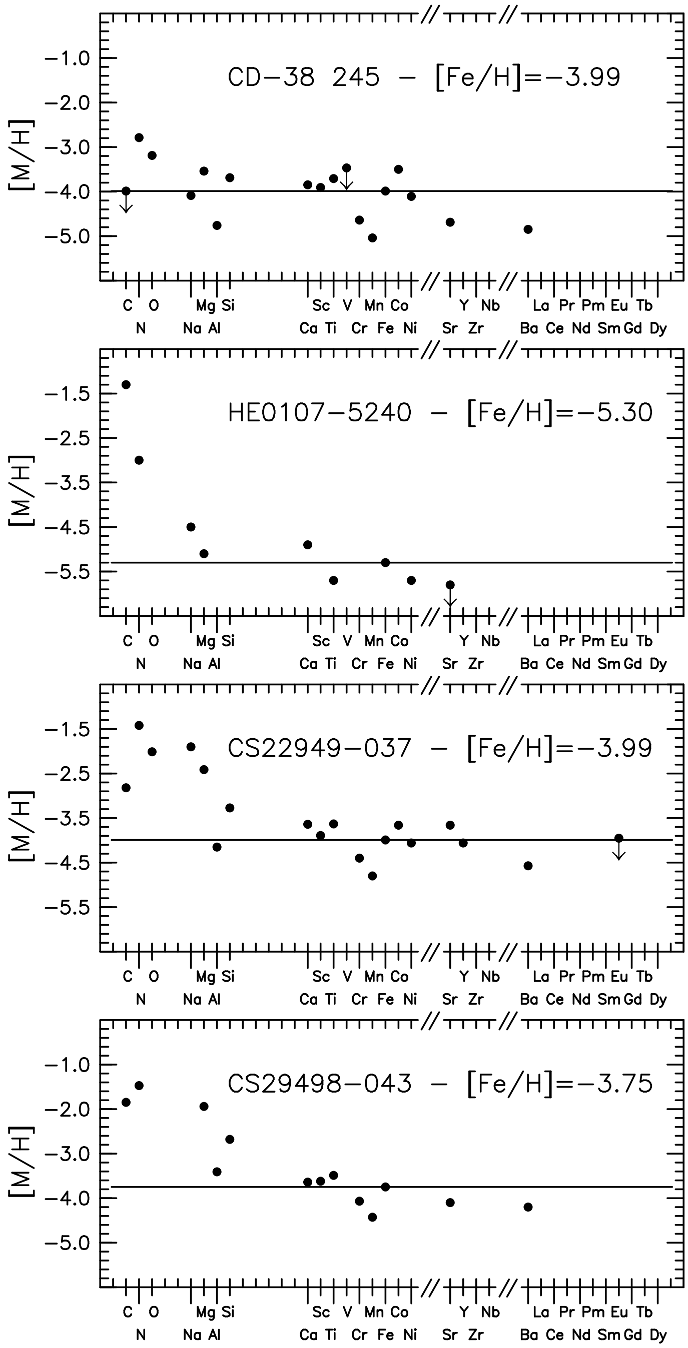

Fig. 1.8. Abundance relative to hydrogen for CD–38°245 and three extremely metal-poor, CNO-enhanced objects, HE 0107–5240, CS 22949–037, and CS 29498–043. (Data from McWilliam et al. 1995; Norris et al. 2001, 2002; Aoki et al. 2002a; Christlieb et al. 2002; Depagne et al. 2002; Bessell 2004.)

One has to wonder if any of these agencies is playing a role in the enormous values of [N/Fe] found at [Fe/H] $<$ –3.5. As noted by Carr, Bond, & Arnett (1984), the essential feature of the very massive ($M \gtrsim 200\ M_\odot$) objects is their potential to "pass carbon and oxygen from the helium-burning core through the hydrogen-burning shell, in such a way that it is CNO processed to nitrogen before entering the hydrogen envelope." Also of particular interest is the work of Fryer, Woosley, & Heger (2001), who consider the evolution of rotating zero-heavy element objects of mass 250 and 300 $M_\odot$. As noted by Norris et al. (2002) these models seem quite capable of explaining the observed C, N, and O abundances in CS 22949–037. That said, it should be noted it is not clear whether the observed α-element enhancements can be produced by such objects. Finally, the role of rotation in very metal-poor stars with $M \leq 60\ M_\odot$ in producing nitrogen enhancements has been considered by Meynet & Maeder (2002). These models seem incapable of explaining the large excesses being considered here.

1.7 Conclusion

In the half century since Chamberlain & Aller (1951) first reported the existence of metal-poor stars, objects having greater and greater deficiency have been discovered, with the most extreme case having [Fe/H] = –5.3—close to the observational limit that Iben (1983) suggests is set by accretion from the interstellar medium. The subject is still, however, in its infancy when it comes to understanding the details and implications of the abundance patterns of extremely metal-poor stars, defined by, say, [Fe/H] $<$ –3.5. With the increasing number of extremely metal-poor candidates currently being discovered by the HK and HES surveys, together with the existing high-dispersion spectrographs on 8 and 10-meter telescopes, one should expect a rapid increase in our understanding of these objects in the coming decade, together with closer insight into the nature of the first heavy element-producing objects.

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