Abundances in Very Metal-Poor Stars

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Abstract: Metal-poor stars provide information on the characteristics and chemical evolution of the halo population of the Galaxy, the first epoch of

star formation and Galaxy formation (not just locally but with relevance to high-redshift objects), and big bang nucleosynthesis. This review looks at recent developments in this subject.

1 Introduction

Halo stars can be viewed in several contexts. They constitute the oldest and most extended stellar population *known* in the Galaxy. As probes of Galactic chemical evolution (GCE), they are the oldest objects and have the lowest metallicities, and hence provide the first data in the evolutionary sequence. In a third context, the early evolution of the universe, Figure 1 shows the metallicity distributions of 36 halo globular clusters (Laird et al. 1988a), 373 halo field stars (Laird, Carney & Latham 1988b; Ryan & Norris 1991) and 34 damped Lyman-α systems (DLAs; Pettini et al. 1997). Not only are the field and cluster metallicity distributions comparable, they are *lower* in metallicity than the DLAs having redshifts $z \sim$ 1–3. That is, very metal poor stars are amongst the lowest metallicity objects in the known universe.

The surprise some people express in discovering that DLAs are generally more metal rich than the Galactic halo emphasises that our knowledge of the DLAs has yet to mature. There is ongoing debate about what they really are, possibilities including:

- spiral disks/protodisks/thick disks (e.g. Wolfe et al. 1986; Lu et al. 1996)
- dwarf galaxies (Pettini, Boksenberg & Hunstead 1990; Pettini et al. 1999a)
- ejecta from dwarf galaxies (Nulsen, Barcons & Fabian 1998).

In examining Galactic stars, we have the advantage of studying objects with reasonably well understood histories and physical states, whose spectra are not blended, and whose abundances, which are measurable for many elements, are unaffected by depletion onto dust grains.

The value of halo stars for studying early epochs of the universe may be further illustrated by considering additional objects in metallicity-redshift space. Figure 2 shows a number of Galactic and high-redshift objects, along with three GCE models assuming outflow, no outflow (closed box) and inflow for Galaxy formation assumed to begin at redshift $z = 5$ (Edmunds & Phillipps 1997). (A Hubble constant $H_0 = 50$ km s^{-1} Mpc^{-1} and flat cosmology [deceleration parameter $q_0 = 0.5$] were used to establish the age-redshift relation.) The disk star sequence and bulge of the Galaxy are based on the observations of Edvardsson et al. (1993) and Sadler, Rich & Terndrup (1996). The high-redshift objects are the DLAs from Pettini et al. (1997)

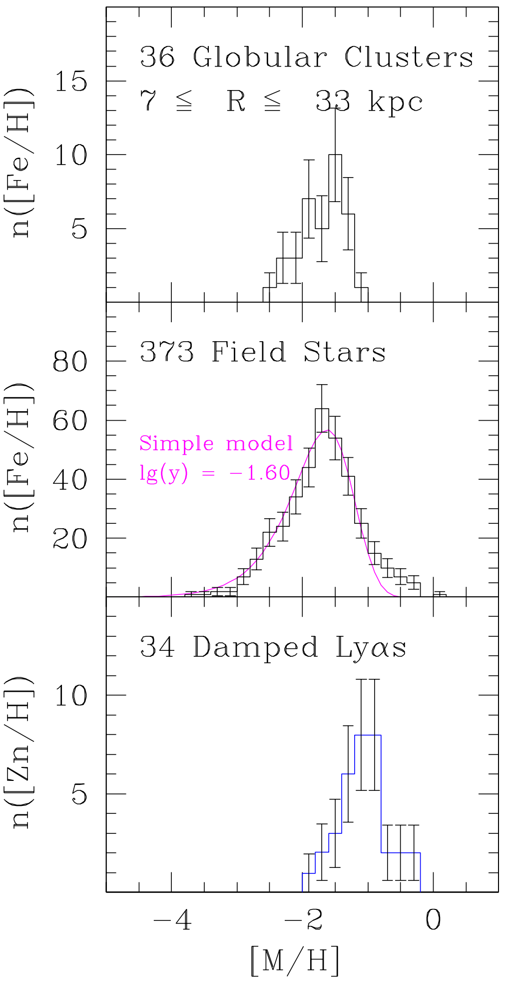

Figure 1: Metallicity distributions of Galactic halo globular clusters, Galactic halo field stars, and Damped Lyman-α quasar absorption line systems.

binned in redshift, Molaro et al. (1996) and Lu et al. (1996), a region corresponding to the Lyman-α forest (Hellsten et al. 1997), and one Lyman break galaxy (LBG) from Pettini et al. (1999b). The redshift distribution in the Hubble Deep Field (Bouwens, Broadhurst & Silk 1998) is shown as an inset against the vertical axis. In adjoining panels are the extinction-corrected star formation rate (Steidel et al. 1999) and the quasar space density (Warren, Hewitt & Osmer 1994) whose steep fall at redshift $z > 3.5$ indicates that these objects were still forming prior to this epoch, presumably along with galaxies. Several points can be noted.

- The occurrence of systems covering a wide metallicity range at the same high redshift — the Lyman-α forest at $-3 < [\mathrm{M/H}] < -2$, DLAs at $-2 < [\mathrm{M/H}] < -1$, and a Lyman break galaxy at $[\mathrm{M/H}] > -1$ — suggests that we are probing diverse objects, not necessarily an evolutionary sequence, in the high redshift universe.
- The overlapping of high redshift and Galactic objects in this epoch-metallicity plane (redshift translates to epoch), e.g. the LBG and the Galactic bulge, and the Lyman-α forest and metal poor stars, emphasises that these objects provide complementary views on the formation and evolution of galaxies. No one class should be considered in isolation from the others.
- Galactic stars with $[\mathrm{Fe/H}] < -3$, corresponding to $z \gtrsim 4$–5, uniquely probe the earliest star formation events. A high level of detail is achievable because many elements can be measured

in well understood objects. Furthermore, the elements in these objects owe their existence to very few previous generations of stars, possibly only one (Ryan, Norris & Bessell 1991). They mark the beginning of GCE, and as such will be the main topic of this review.

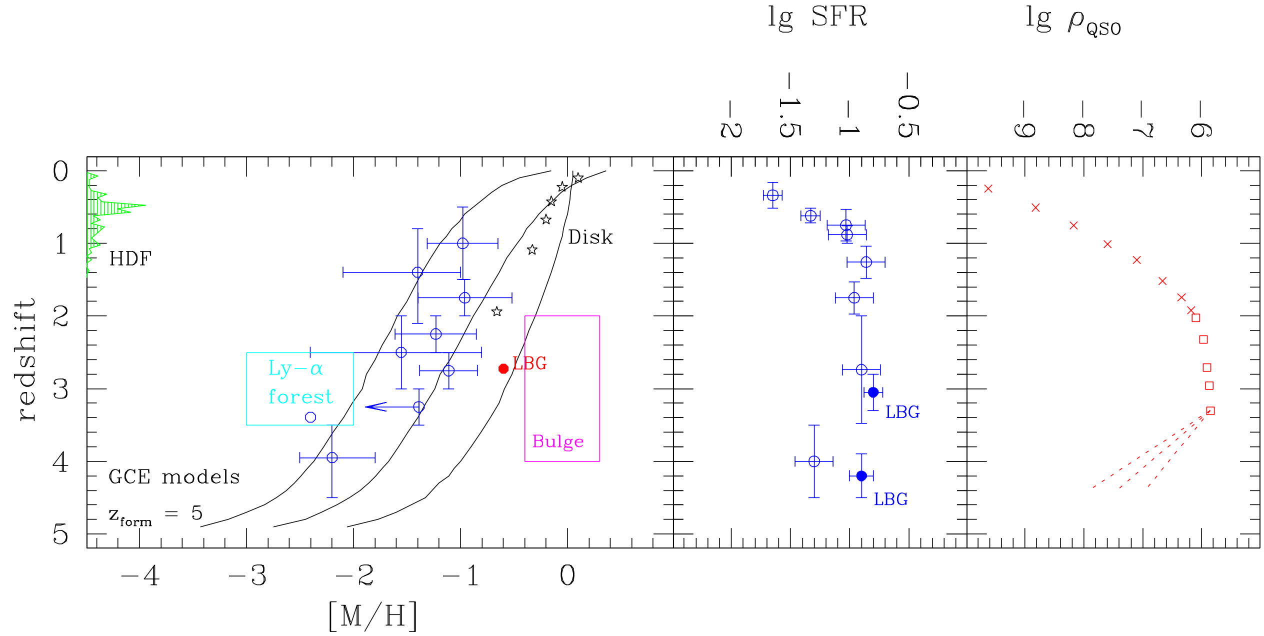

Figure 2: (a): Galactic and high-redshift objects in the redshift–metallicity plane, the former located at their redshift of formation (assuming $H_0 = 50$ km s^{-1} Mpc^{-1}). *solid curves* = GCE models; *open circles* = DLAs; *stars* = disk star sequence; *solid circle* = LBG. (b) Star formation history of extragalactic objects. (c) Quasar density distribution. (See text for discussion.)

2 How Many Supernovae Make a Population II Star?

Disk stars formed from gas enriched by many previous generations of stars. Population II stars formed earlier and have lower metallicities, consistent with fewer supernovae being involved. A simple closed box model of GCE (e.g. Searle & Sargent 1972; Pagel & Patchett 1975) establishes a framework based on a single free parameter — the fraction of enriched matter returned to the interstellar medium by a stellar generation, known as the yield. No check is kept on timescales or stellar generations; with instantaneous processing and complete mixing, the model follows essentially the average evolution of a galaxy. Despite these gross simplifications, the model compares very favourably with the metallicity distribution of the Galactic halo; Figure 1 compares halo field star data with a simple model with yield $y = 10^{-1.6}$ (Ryan & Norris 1991). However, models of this type are incapable of indicating how many supernovae are required to enrich a stellar Population to a given metallicity, and alternatives treating the formation and evolution of stars more realistically had to be developed.

One model which considered individual generations of stars was Searle's (1977) stochastic model, which postulated that separate star forming fragments underwent star formation according to Poisson statistics, the mean number of enrichment events increasing with time and the enrichment from each being constant. This model again has only one free parameter, the mean number of enrichments prior to the termination of star formation, μ, but it is capable of quantifying the number of supernovae involved. Its metallicity distribution is broadly similar to that of the simple model. Applied to halo field stars, Searle's stochastic model was not obviously better than the simple model, but did give a marginally better fit to the globular cluster distribution, implying a mean of ten enrichments per fragment (Ryan & Norris 1991). With the mean metallicity of the halo globular clusters being [Fe/H] $\simeq -1.5$, this suggested that a single event could enrich a fragment to [Fe/H] $\simeq -2.5$.

Truran (1981) argued that the atmospheres of second generation stars would contain r- but no s-process isotopes, due to the latter's secondary nature, whereas subsequent generations would contain both types. Although it was not clear at which metallicity this would be achieved, it forced people to think about the first few generations of stars.[1] Large star-to-star variations in the neutron-capture abundances of stars with [Fe/H] < -2.5 (e.g. Gilroy et al. 1988) suggested that prior nucleosynthesis involved small numbers of supernovae (SN). Related observations of Sr led Ryan et al. (1991) to consider stochastic enrichment by only a few stellar generations, and to calculate the metallicity produced by single supernova as [Fe/H] $= -3.8$, based on a typical SN II progenitor mass of 25 $\mathrm{M}_\odot$ and an assumed primordial cloud mass of 10^6 $\mathrm{M}_\odot$.[2] This coincided with the observed onset of huge abundance variations of strontium (by a factor of 100 or more), and was consistent with the lowest stellar metallicities then observed.[3]

Star-to-star differences in neutron-capture element abundances at the lowest metallicities also required that chemical inhomogeneities existed around the time these stars were forming. Audouze & Silk (1995) showed further that mixing timescales in the halo were sufficiently long that inhomogeneities of this type would not be erased on the timescale over which stars would form, supporting the proposition that the progeny of the first supernovae would be found around this metallicity. Mounting examples of neutron-capture element variations from star to star (e.g. Norris, Peterson & Beers 1993; McWilliam et al. 1995; Ryan 1996; Ryan et al. 1996) strengthened the view that the most metal-poor stars exhibit the ejecta of very small numbers of supernova.

The need to integrate small number statistics of the first supernova with GCE models led Ryan, Norris & Beers (1996) to examine the enrichment sphere of a single SN in a primordial cloud. Adopting the supernova remnant (SNR) model of Cioffi, McKee & Bertschinger (1988), they calculated the cloud mass with which the SN ejecta would mix as

$$m_{\mathrm{ISM}} = 3.4 \times 10^4 E_{51}^{0.95} n_0^{-0.10} \zeta_m^{-0.15} (\beta C_{06})^{-1.29} \quad \mathrm{M}_\odot,$$

where E, n, ζ, and βC_{06} refer to the explosion energy, cloud density, cloud metallicity, and shock speed in appropriate units. The main features of this result were:

- the mass of gas enriched is almost independent of the cloud characteristics (n, ζ) and depends strongly (almost linearly) on the energy of the SN;
- the typical enriched mass of the cloud would be 7×10^4 $\mathrm{M}_\odot$;
- the typical metallicity following this first enrichment would be [Fe/H] $= -2.7$, matching (perhaps coincidentally) the changes in the behaviour of iron-peak and neutron-capture elements and the lowest metallicity globular clusters.

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[1] It is uncertain that we will actually see a clear division between r- and s-process elements in second versus third generation stars, because most neutron-capture elements have contributions from both the s- and r-process.

[2] The SN mass was a compromise between higher mass stars being rarer and lower mass stars having lower yields. The cloud mass was based on large globular clusters, giant molecular clouds, and the collapse of metal poor gas.

[3] The vanishing of Sr in some stars at this metallicity suggested to me, at the time, that Truran's mechanism was possibly being observed, and that genuine second generation stars were being identified. However, the more recent availability of data on Ba has altered my views on this; see Footnote 1 and later sections of this paper.

Many other GCE models have been developed that incorporate the initial mass function, the mass-dependence of stellar lifetimes, the mass- and metallicity-dependence of supernova and stellar-wind yields, and more. In the light of observational and theoretical reasons for expecting the first star forming regions to be poorly mixed, new GCE models have been forthcoming that include SNR physics and inhomogeneous mixing (e.g. Shigeyama & Tsujimoto 1998; Tsujimoto & Shigeyama 1998; Ishimaru & Wanajo 1999a; Argast & Samland 1999), against which the abundances of very metal poor stars can be compared. It is then possible to invert the problem and use the observed abundances to constrain the model inputs. As stars at these low abundances are believed to be second generation stars, of particular interest will be the shape of the IMF of their progenitors (Population III stars!), the mass limits for the production of SN of Population III stars, and the yields of individual Population III objects.

3 Abundances: Can You Believe What You Read?

Weak lines have the greatest sensitivity to abundance and the least sensitivity to uncertain parameters of the stellar atmosphere. However, the lines that are weak in very metal poor stars are strong in the sun, so completely different lines are measured in the two cases, the former often also being of lower excitation potential and possibly of a different ionisation state. Photometric temperature calibrations and stellar atmosphere models also depend on metallicity. These factors give rise to potential systematic differences between analyses conducted for metal rich compared to metal poor stars. The overall rarity of spectral lines in metal poor stars also limits consistency checks between several lines of one element. There can also be substantial differences in the approaches of investigators, who may adopt different reference solar abundances, model atmosphere grids, and atmospheric parameters. Differences of 10% in the equivalent widths measured in two studies of one star are not uncommon. Differences of 0.2 dex in the absolute abundances can accumulate through these effects.

Fortunately, for many species relative abundances (ratios) [X/Fe] are less susceptible to errors than [X/H]; although errors in [Fe/H] better than 0.10 dex are rare, [X/Fe] can often be believed at the level of 0.05 dex (though in some cases only 0.15 dex may be achieved). Homogeneous studies, where abundances are derived almost identically for all stars, can achieve better internal accuracy.

Additional errors can arise from the assumptions of the analysis:

- Effective temperature scales are a large source of error. Infra-red flux method (IRFM) temperatures, often argued to be preferable to other photometric calibrations, are now available for many halo stars (Alonso, Arribas & Martínez-Roger 1996), although the uncertainties on any individual star are currently large.
- Collisional damping constants have improved to the extent that *strong* lines may now provide more reliable abundances than *weak* lines (Anstee, O'Mara & Ross 1997). Damping constants for many neutral transitions have been published (Anstee & O'Mara 1995; Barklem & O'Mara 1997,1998; Barklem, O'Mara & Ross 1998); comparisons with older computations are presented elsewhere (Ryan 1998).
- Corrections for non-LTE have been published for several elements: e.g. Li (Carlsson et al. 1994; Pavlenko & Magazzu 1996), Be (García López, Severino & Gomez 1995), B (Kiselman 1994; Kiselman & Carlsson 1996), O (Kiselman 1991), Na (Baumüller, Butler & Gehren 1998), Mg (Zhao, Butler & Gehren 1998), Al (Baumüller & Gehren 1997), and Ba (Mashonkina, Gehren & Bikmaev 1999).
- 3-D hydrodynamical models are being computed to investigate the errors introduced by 1-D models. Preliminary work signals some interesting results (Asplund et al. 1999), including the

primordial Li abundance having been overestimated.

4 The Lightest Elements

The primordial and spallative elements Li, Be, and B will be thoroughly considered by IAU Symposium 198. In the context of globular clusters versus field stars (see Figure 3), it is useful to compare M92 subgiants (Boesgaard et al. 1998) and field halo turnoff stars (Ryan, Norris & Beers 1999). The latter show no intrinsic spread ($\sigma_{\mathrm{int}} < 0.02$ dex) once a small metallicity dependence (believed to be due to GCE) is taken into account, whereas M92 shows a range of Li. This suggests a difference between the field and globular cluster populations, presumably related to their very different environments, specifically the stellar density. Although single stars seldom interact, protostellar disks may have done so in nascent globular clusters but not in lower density clusters destined ultimately to produce field stars (Kraft 1998, private communication). Such speculation falls short, however, of explaining why the M92 subgiants might have a higher Li spread than in the field. Boesgaard et al. favoured rotationally-induced turbulence resulting in a spread of Li depletion factors from a higher initial value. One might imagine that different angular momentum histories of cluster and field stars could lead to differences of this sort, though the extreme thinness of the field star A(Li) distribution (Ryan et al. 1999) is a lingering difficulty with that scenario.

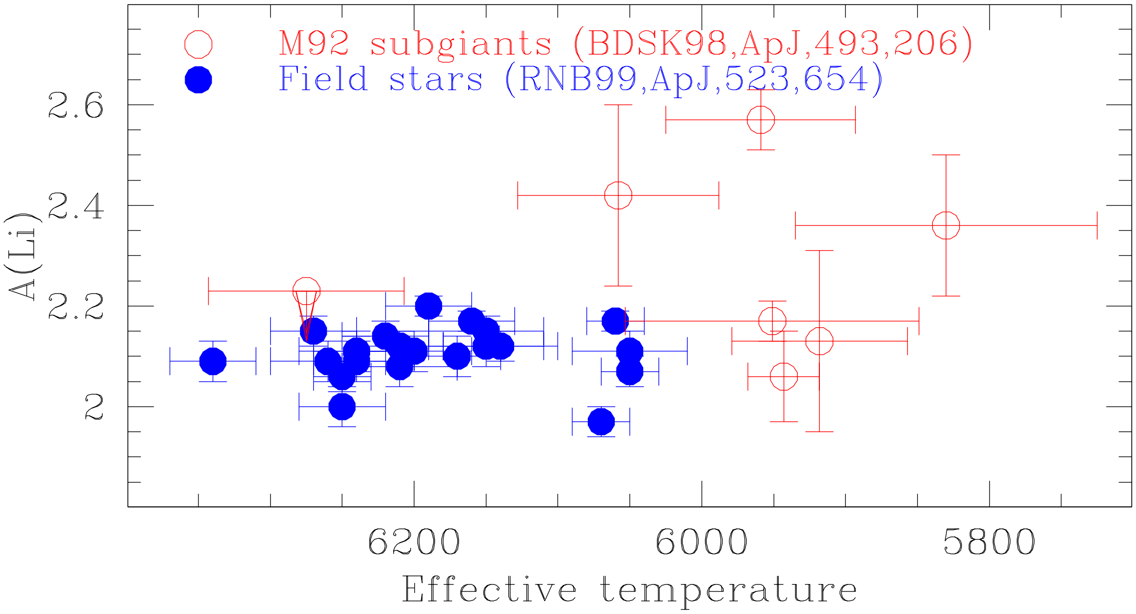

Figure 3: Lithium abundances in very metal-poor halo field stars near the turnoff, compared with globular cluster subgiants in M92.

5 Intermediate-Mass Elements

As two of the most abundant metals, C and O are very important in stellar evolution and as diagnostics of GCE, but our views of O have undergone numerous revisions in the last decade. Measurements are presented in Figure 4, which isolates giants from dwarfs, and shows separately the abundances derived from the forbidden lines [O I], near-infrared triplet O I, and ultraviolet OH lines.

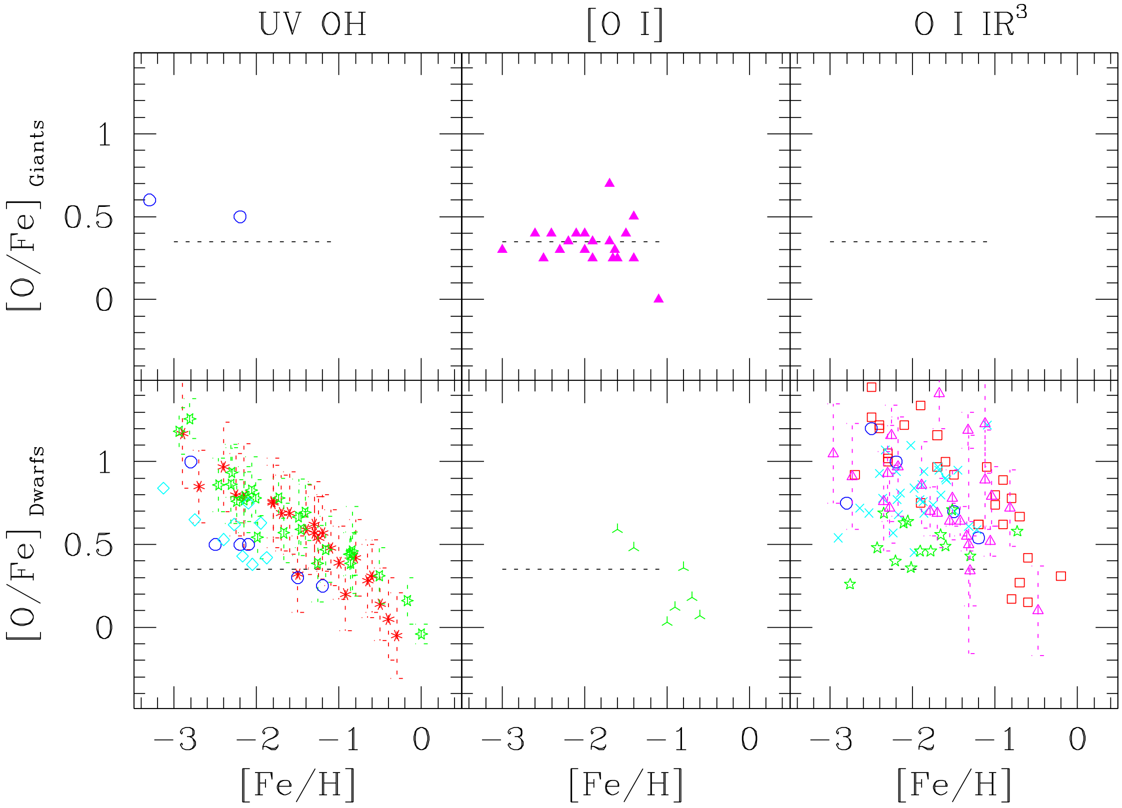

Figure 4: Oxygen in metal poor field stars. *circles:* Bessell, Sutherland & Ruan 1991; *filled triangles:* Barbuy 1988; *diamonds:* Nissen et al. 1994; *six-pointed stars:* Boesgaard et al. 1999; *asterisks:* Israelian, García Lopéz & Rebolo 1998; *inverted 'Y's:* Spite & Spite 1991; *squares:* Abia & Rebolo 1989; *crosses:* Tomkin et al. 1992; *five-pointed stars:* King 1993; *open triangles:* Cavallo, Pilachowski & Rebolo 1997.

Barbuy (1988), studying the forbidden line in giants, found a result similar to that for α-elements in the halo, i.e. an overabundance by 0.3–0.4 dex irrespective of metallicity, shown as a dotted line in Figure 4. Results for the infra-red triplet, however, have been inconsistent. Abia & Rebolo (1989) found a progressive increase in the overabundance, approaching 1.5 dex at $[\mathrm{Fe/H}] = -3$. Subsequent studies found different results, arguing inconsistencies between different lines (Magain 1988), T_{eff} dependences, and errors in the T_{eff} scale and equivalent widths. The most recent studies used the UV OH lines, Israelian et al. (1998) and Boesgaard et al. (1999) finding almost identical trends towards high O overabundances in the most metal-poor stars. Note that although Bessell, Sutherland & Ruan (1991) concluded that their OH line measurements were consistent with Barbuy's (1988) giants, Bessell et al's dwarfs and Nissen et al's (1994) almost fit the recent OH trend, albeit displaced by $\simeq -0.3$ dex. Gratton (1999) warns of the difficulty of fitting the continuum near the UV OH lines for the more metal-rich stars, the need for accurate molecular line parameters, and the need to apply NLTE corrections for the high-excitation O I triplet. The lack of agreement between measurements of the triplet (Figure 4) attests to the difficulties in using these lines.

Barbuy's finding that O behaves like the α-elements was attractive under the paradigm that copious production of Fe in SN Ia was responsible for the decrease in [α/Fe] at [Fe/H] > -1. However, O and the α elements are formed separately, so their yields relative to Fe do not have to exhibit the same dependence on metallicity. The difficulty posed by the observations is that current stellar models predict O and α to evolve together, and do not show high overabundances of [O/Fe]. The models of Timmes, Woosley & Weaver (1995), for example, achieve [O/Fe] $= +0.4$ at [Fe/H] $\simeq -3$, or even $+0.6$ if the iron yield is halved, but they don't reach 1.0 as the OH data do. Furthermore, it is not sufficient to claim that the Fe yields could be wrong, for while they *could* be wrong, that would not help the problem with O; the OH observations require that [O/α] is also strongly dependent upon metallicity, and that is not seen in the models either. So, if the theoretical yields are to fit the OH line data, significantly higher O production will be required, irrespective of what changes are made to Fe.

Carbon and nitrogen measurements in very metal-poor stars (Israelian & Rebolo 1999) generally give approximately solar ratios. However, there have also been significant numbers of C-rich stars found at the lowest iron abundances (Beers, Preston & Shectman 1992). Possibly as many as 10% of stars with [Fe/H] < -2 have high CH-band strengths. While one of these, CS 22892-052, has huge r-process element overabundances (Sneden et al. 1994, 1996), the majority exhibit s-process patterns (Norris, Ryan & Beers 1997a; Barbuy et al. 1997; Norris et al. 2000). The high C abundances are not predicted by theoretical yields of supernovae (e.g. Timmes et al. 1995), but might be explained by enrichment of the early halo by mass loss from high mass Population III stars which have synthesized C via the triple-alpha process and mixed it to their surfaces (e.g. Marigo 1999). The frequency of C-rich stars and their tendency to be accompanied by s-process rather than r-process heavy element signatures (suggestive of AGB star evolution rather than supernovae) will be important to understanding their origin. (Note, however, that not all C-rich stars exhibit heavy element anomalies [Norris, Ryan & Beers 1997b]).

The α-elements (Mg, Si, Ca) have fairly uniform overabundances relative to iron extending down to the lowest metallicities (Ryan et al. 1991; Norris et al. 1993; McWilliam et al. 1995; Ryan et al. 1996). Recent studies have begun to concentrate on star-to-star variations, with King (1997), Carney et al. (1997), and Nissen & Schuster (1997) identifying stars with low [α/Fe] ratios, predominantly retrograde kinematics, and young ages. The low [α/Fe] ratios are reminiscent of those proposed by Matteucci & Brocatto (1990) and Gilmore & Wyse (1991) for star formation in dwarf galaxies where star formation ceased before metallicities typical of Galactic disk stars were reached, so that the appearance of SN Ia would lead to low [α/Fe] ratios even at metallicities typical of halo stars.[4] Similarly, the dual halo models of Zinn (1993), based on globular clusters, and Norris (1994), based on field stars, fit with the characteristics of the stars now observed. Clearly there is still much to learn about the Galactic halo by exploiting relative abundances.

For [Na/Fe] and [Mg/Fe], Hanson et al. (1998) have found different behaviours for globular cluster and field stars, even though they have examined the same evolutionary states in each sample. They find the two elements to be positively correlated in the field, signifying common production, and find correlations with kinematics in the sense that the youngest stars (inferred from lower [Na/Fe] and [Mg/Fe] values) have predominantly retrograde kinematics. In clusters, on the other hand, they find overall an anti-correlation of [Na/Fe] and [Mg/Fe] suggestive of the proton-capture chain having been active (converting Ne to Na, and Mg to Al, during H-burning via the CNO cycle). The appearance at the stellar surface of these changes requires

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[4] A possible conflict is raised by the work of Kobayashi et al. (1998) who propose that the SN Ia mechanism would have lower efficiency at [Fe/H] < -1 due to the weaker winds in metal-deficient stars.

deep mixing, so one may conclude that deep mixing has occurred in the globular cluster giants but not in the field giants *even at the same evolutionary state.* Why this should be so has yet to be resolved; the Li results (§4) may be related.

6 The Iron-Peak Elements

The iron-peak elements most easily observed in very metal-poor stars are Sc, Ti, Cr, Mn, Fe, Co, and Ni. For stars with $[\mathrm{Fe/H}] > -2.5$, most of these species exhibit solar abundance ratios. One exception is Mn, which is underabundant by $\sim$0.3 dex in halo stars. A second exception is Ti, but whether or not Ti should be included in the iron-peak group at all is unclear (e.g. Lambert 1987). While it is believed to be produced in the same region of stars as the other iron-peak elements, its abundance appears more like the α-elements in that it is overabundant by $\sim$0.3–0.4 dex in stars with $[\mathrm{Fe/H}] < -1$.[5] McWilliam et al. (1995) and Ryan et al. (1996) showed that although the Sc and Ti abundance trends persist to the lowest metallicities known, $[\mathrm{Fe/H}] = -4.0$, Mn and Cr become very underabundant in stars with $[\mathrm{Fe/H} < -2.5$, while in the same objects Co becomes overabundant. (See Figure 5.) There is also limited evidence for Ni overabundances in some of these objects. These changes were not predicted by supernova computations, and provide a recent example of observations leading theory in new directions.

The iron-peak species are synthesised deep in the star, close to mass-cut (the division between matter ejected from the supernova and that which collapses onto the stellar remnant). Supernova calculations are unable to eject material naturally from the physical conditions of the star, foreshadowing the difficulty of accurately predicting the yields of the iron-peak species which depend sensitively on the explosive conditions. The position of the mass cut cannot be predicted, but must be constrained by the observed abundances. Cr and Mn are produced only in a shell towards the outside of the Fe (and Ti) core, while Co and Ni are produced internal to that, so the resulting relative yields of iron-peak species can be adjusted by moving the mass-cut even slightly within the star (e.g. Nakamura et al. 1999).

Efforts to understand the abundance trends have focussed on the possible α-rich freeze-out (Woosley & Hoffman 1992; McWilliam et al. 1995), the location of the mass-cut (Nakamura et al. 1999), and the dependence of yields on stellar mass, metallicity, and neutron excess (Nakamura et al. 1999; Hix & Thielemann 1996). The explanation must account for a handful of elements with different behaviours, whilst not distorting the [X/Fe] ratios of species such as Mg, Si, and Ca which are formed well outside the mass-cut. This is particularly challenging for explanations which alter the Fe yield! Progress may increase when 3D hydrodynamical models provide more realistic treatments of the supernova explosion (e.g. Müller, Fryxell & Arnett 1991). Observational evidence for mixing of material from the mass-cut to the photosphere appears to be growing (Stathakis 1996; Fassia et al. 1998), and provides an additional set of clues and constraints as we seek more realistic supernova models.

7 Neutron-Capture Elements

Spite & Spite (1978) showed from observations of Ba (of mixed s- and r-process origin) and Eu (essentially pure r-process) that the Ba in halo stars owed its origin primarily to the r-process. Truran (1981) provided a theoretical insight into the relative contributions of the processes by

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[5] Truran (1999, private communication) reports that the experimental $^{44}\mathrm{Ti}(\alpha,\mathrm{p})^{47}\mathrm{V}$ rate is five times higher than the theoretical one used in previous nucleosynthesis calculations, so the theoretical yields of some iron-peak elements will be subject to revision.

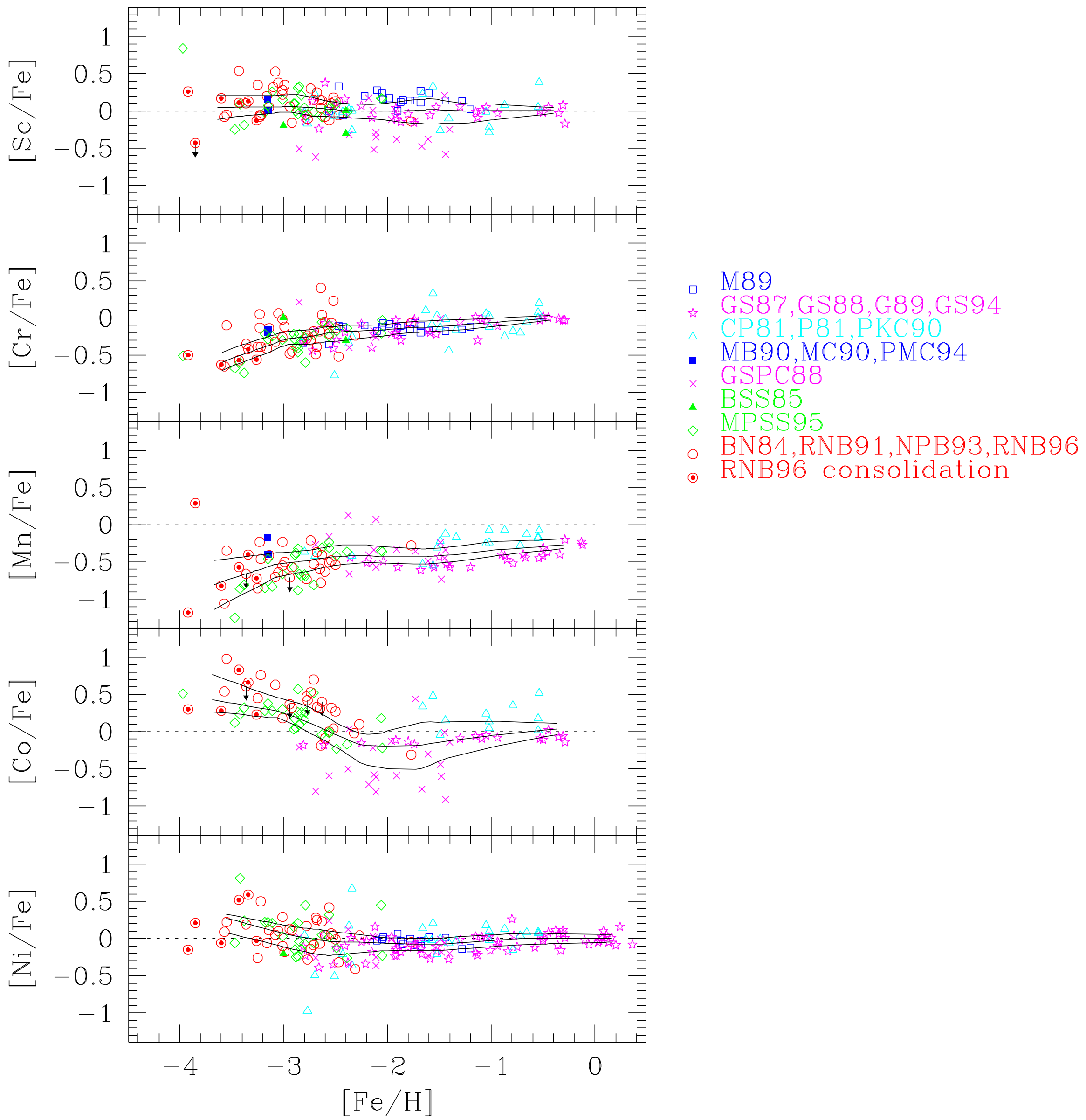

Figure 5: Abundances of iron-peak elements in very metal-poor halo field stars. Solid curves are robust estimates of the mean and quartiles. (See text and references for details.)

examining the roles of seed nuclei, and argued that the s-process should be viewed as a secondary process while the r-process was primary, and thus that first generation — Population III — stars would not execute the s-process. Gilroy et al. (1988) showed that the neutron-capture elements exhibited abundance patterns more consistent with the r-process than the s-process. McWilliam et al. (1995, 1998) extended the Ba and Eu comparison to the lowest metallicities ([Fe/H] = −4), confirming the existence of r-process (rather than s-process) ratios.

An alternative means of examining the s- and r-process contributions would be via isotope ratios. Heavy element isotope lines are invariably blended in stellar spectra, but in a small number of cases they give rise to significant differences in the line profile allowing constraints to be placed on the isotope ratios. Magain (1995) obtained observations of this effect, and in HD 140283, at [Fe/H] = −2.6, inferred an s-process rather than r-process pattern for Ba.

This result was unexpected given the r-process framework that had been established over the preceeding nearly 20 years. In contrast, Gacquer & Francois (1998, private communication) find an r-process signature for this star.

The reliance almost solely on Ba and Eu as diagnostics of the s- vs r-process fractions has been diminished by *HST* data for other important neutron-capture elements having UV spectra. Included in this list are Ag, Pt, Os, and Pb (Crawford et al. 1998; Cowan et al. 1996; Sneden et al. 1998).

Gilroy et al. (1988) also found that neutron-capture elements showed significant star-to-star variations in the most metal poor objects ($[\mathrm{Fe/H}] \lesssim -2.5$), building upon similar cases reported earlier during the decade. The abundance variations are greatest for Sr, where ranges of a factor of more than 100 were found amongst dwarfs (Ryan et al. 1991) and giants (Norris et al. 1993). Moreover, as Figure 6 shows, such extreme variations are *not* shared by Ba, which exhibits a fairly steady trend towards lower [Ba/Fe] at lower [Fe/H].

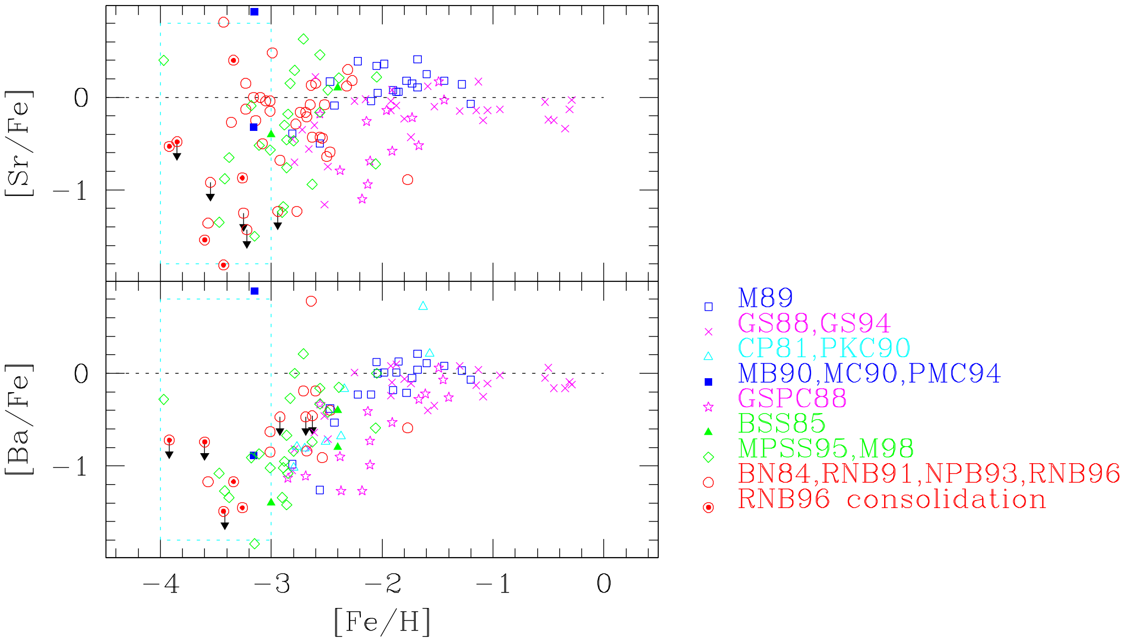

Figure 6: Abundances of Sr and Ba in halo stars. The dashed box outlines the same region of [X/Fe] and [Fe/H] in each plot. Whereas [Sr/Fe] exhibits a range by a factor of more than 100, [Ba/Fe] has a well-behaved trend towards lower values at the lowest [Fe/H].

Reconciling Sr and Ba is a challenge. If the r-process alone is responsible for their synthesis in very metal-poor halo stars, then Figure 6 tells us that the r-process cannot be universal. Whilst there is no theoretical reason why it *must* be universal, halo star neutron-capture element abundance patterns generally resemble the r-process contribution in the sun (e.g. Gilroy et al. 1988; McWilliam et al. 1995; Cowan et al. 1995, Sneden et al. 1996). This cannot be ignored, even if non-uniqueness (Goriely & Arnould 1997) is possible. Hypothesising that the lower envelope to the [Sr/Fe] observations is the "normal" r-process behaviour, corresponding to a universal [Ba/Sr] r-process value, we seek a source of additional Sr in the lowest metallicity objects. Figure 6 emphasises that the process responsible must involve low neutron exposures that synthesise only species around the atomic number of Sr. Other species near Sr are also enhanced in these high Sr stars (Ryan et al. 1996, 2000; see Figure 7.) Whilst the weak s-process would produce primarily low atomic-numbered neutron-capture species, and would be active in normal high mass (>15 $M_\odot$) stars, the difficulties related to the lack of seed nuclei and a suitable neutron source would severely hamper this in low metallicity stars. It may be necessary to look for a new, low-neutron-exposure r-process (Ishimaru & Wanajo 1999b), reflecting two different types of core collapse supernovae.

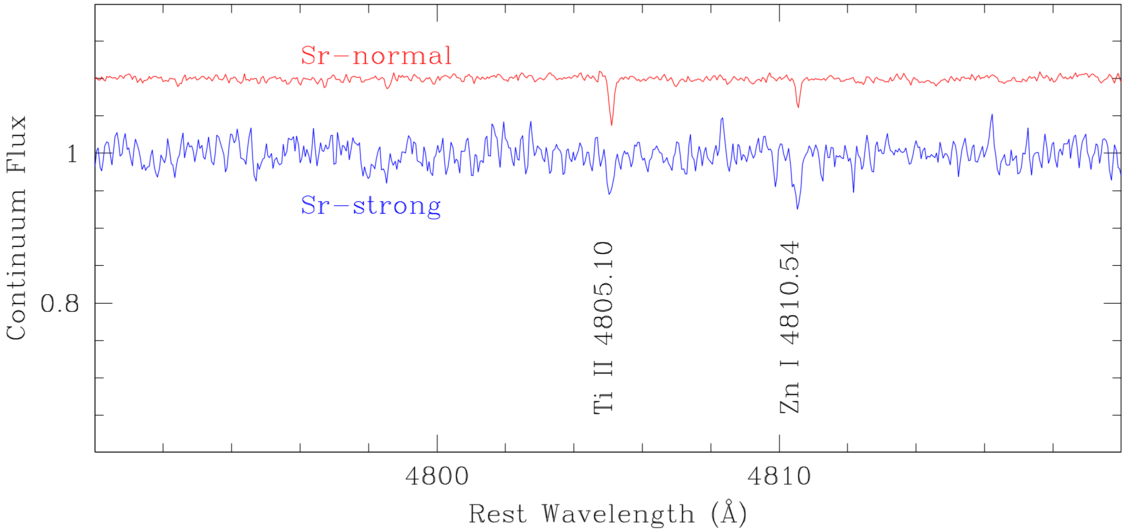

Figure 7: Spectra of Fe and Zn lines in Sr-rich (lower) and Sr-normal (upper) stars. The investigation of other low-atomic-number neutron-capture elements indicates that these too are overabundant in the Sr-rich stars, as expected for a low-neutron-exposure process (Ryan et al. 2000).

GCE models need to reproduce the climb in [Ba/Fe] and [Eu/Fe] for stars with $[\mathrm{Fe/H}] < -2$, which suggests that these species are not produced abundantly in the most massive metal-poor supernovae, for if they were then they would exhibit higher ratios (to iron) even in the lowest metallicity stars (e.g. Mathews & Cowan 1990). Mathews & Cowan associated their production with 10–11 $M_\odot$ stars. Although the evolution in their models is now seen to be too steep for today's data, the concept of low-mass stars being responsible has survived, and a more gradual emergence is seen in the models of Travaglio et al. (1999) which use a mass range 8–10 $M_\odot$ for the process. Travaglio et al. also treat the enrichment of the cloud inhomogeneously, along the lines described in §2 of this review (also Ishimaru & Wanajo 1999a).

The final comments on the neutron-capture elements are reserved for the atypical r-process-rich star, CS 22892-052. Assuming that the neutron-capture elements in this star are present in the same proportions as the r-process contribution in the sun, Cowan et al. (1997) derive an age of 17±4 Gyr, based on the radioactive Th abundance. This is consistent with current estimates of globular cluster ages from isochrone fitting, of around $12.8^{+4.2}_{-2.8}$ Gyr (Chaboyer 1999). Improved data and GCE models will hopefully reduce the errors to provide a chronometer of better accuracy than the globular cluster technique.

8 Final Comments and Summary

Stars with $[\mathrm{Fe/H}] < -3$ formed at the earliest epochs of star formation, corresponding to redshifts $z \gtrsim 4$. They formed from gas clouds enriched by single supernovae, and hence allow us to investigate the first (Population III) stars which enriched primordial (big bang) material with heavy elements. Even though that stellar population was small in number and no surviving example has been detected today, it is still possible to investigate its mass function and evolution via the nucleosynthetic yields frozen into the next generation of stars, the extremely metal-poor Population II stars.

Extremely metal-poor stars exist in two main environments — the field and globular clusters — and the two appear not to be identical. Building on previous differences (e.g. CN variations which appear more common in globular cluster than field stars), we now see a spread of Li in M92 and evidence of deep mixing in globular cluster giants (via the proton-chain signature) which do not appear in the field. These may indicate that the clusters in which today's field stars formed were not the same as the dense globular clusters that survive to the present. In using Population II objects to study GCE, it would then seem safer to rely on field stars which sample a much larger volume of the Galaxy and are less likely to have interacted with other objects in a dense environment, rather than trusting objects which sample the chemical evolution of a small region of space with high stellar density.

Recent measurements have highlighted the state of confusion which exists over oxygen abundances in halo stars. Meanwhile, some elements have shown remarkably robust abundance patterns as more metal-deficient stars are sampled, such as Ti (though we know not why!). Greater accuracy has enabled star-to-star abundance variations to be examined in intermediate atomic-mass elements, shedding new light on the chemical and kinematic composition of the Galaxy, and its evolution. Likewise, the huge abundance spread in Sr, but not Ba, is allowing us to probe the nucleosynthesis processes and ultimately the mass function of the first stars. These advances accompany more realistic GCE models that incorporate the stochastic nature of star formation which is potentially of great importance in the earliest epochs where small numbers of supernovae were involved.

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