

ABUNDANCE RATIOS AND GALACTIC CHEMICAL EVOLUTION

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KEY WORDS: abundances, chemical composition, the Galaxy, nucleosynthesis, stars

ABSTRACT

The metallicity of stars in the Galaxy ranges from $[\text{Fe}/\text{H}] = -4$ to $+0.5$ dex, and the solar iron abundance is $\epsilon(\text{Fe}) = 7.51 \pm 0.01$ dex. The average values of $[\text{Fe}/\text{H}]$ in the solar neighborhood, the halo, and Galactic bulge are -0.2 , -1.6 , and -0.2 dex respectively.

Detailed abundance analysis reveals that the Galactic disk, halo, and bulge exhibit unique abundance patterns of O, Mg, Si, Ca, and Ti and neutron-capture elements. These signatures show that environment plays an important role in chemical evolution and that supernovae come in many flavors with a range of element yields.

The 300-fold dispersion in heavy element abundances of the most metal-poor stars suggests incomplete mixing of ejecta from individual supernova, with vastly different yields, in clouds of $\sim 10^6 M_{\odot}$.

The composition of Orion association stars indicates that star-forming regions are significantly self-enriched on time scales of 80 million years. The rapid self-enrichment and inhomogeneous chemical evolution models are required to match observed abundance trends and the dispersion in the age-metallicity relation.

INTRODUCTION

Except for the lightest elements, the history of the chemical composition of the Galaxy is dominated by nucleosynthesis occurring in many generations of stars. Stars of low mass have long lifetimes, some comparable to the age of the Galaxy,

and their envelopes have preserved much of their original chemical composition. These stars are useful because they are fossils containing information about the history of the evolution of chemical abundances in the Galaxy. After the Big Bang, the story of nucleogenesis is concerned mostly with the physics of stellar evolution and nucleosynthesis in stars, with how the environment dictated the kinds of stars that formed to enrich the Galactic gas, and with how the enriched gas mixed with the interstellar medium to form subsequent stellar generations (Hoyle 1954). We can try to understand these processes and chemical evolution from theoretical models, but the best way to learn about the history of the elements in the Galaxy is to look at the fossils.

Time and space do not permit me to discuss in sufficient detail the many exciting developments that have occurred in the area of chemical evolution. Therefore, I restrict myself to areas most closely aligned with my research, which is usually concerned with high-resolution abundance analysis of stars in our Galaxy; in particular I do not discuss all the elements, or families of elements, and some elements may be conspicuous by their absence.

Despite its obvious flaws, a good starting point for developing a mental picture of chemical evolution is the Simple one-zone model (e.g. Schmidt 1963, Searle & Sargent 1972, Pagel & Patchett 1975). The model assumes evolution in a closed system, with generations of stars born out of the interstellar gas (ISM). In each generation, a fraction of the gas is transformed into metals and returned to the ISM; the gas locked up in long-lived low-mass stars and stellar remnants no longer takes part in chemical evolution. Newly synthesized metals from each stellar generation are assumed to be instantaneously recycled back into the ISM and instantaneously mixed throughout the region; thus, in this model, metallicity always increases with time, and the region is perfectly homogeneous at all times.

The ratio of mass of metals ejected to mass locked up, y , is a quantity commonly called the yield. The term yield has another meaning: Supernova (SN) nucleosynthesis theorists use it to refer to the mass of a particular element ejected in a SN model. The yield depends on the mass of metals ejected by stars (usually a function of mass) and the relative frequency of different mass stars born in a stellar generation (this is the initial mass function, or IMF). The mean IMF has been measured empirically (e.g. Scalo 1987) and over Galactic time appears to have been approximately constant; however, for individual molecular clouds, large deviations from the mean IMF occur.

Another chemical evolution parameter is the star formation rate (SFR), which has been postulated to be proportional to some power of the gas density and the total mass density. In the Simple model, the SFR affects the time evolution of the metallicity but does not affect the final metallicity function of the system after the gas has been exhausted.

Given the yield, the metallicity function of long-lived stars for the Simple model is as follows:

$$f(z) = y^{-1} \exp(-z/y)$$

If evolution continues to gas exhaustion, then the Simple model predicts that the average mass fraction of metals of long-lived stars is equal to the yield, $\langle z \rangle = y$. In principle the mean metal content of a stellar system can tell us about the yield. Because the yield is the ratio of mass of metals produced to the mass in low-mass stars per generation, it is sensitive to the IMF: An IMF skewed to high-mass stars would have a higher yield because more stars are massive enough to produce metals as SN, and there are fewer low-mass stars to lock away the gas.

Abundance ratios can serve as a diagnostic of the IMF and SFR parameters and time scale for chemically evolving systems. Tinsley (1979) proposed that type Ia supernovae (SN Ia, resulting from mass accretion by a C-O white dwarf) are the major producers of iron in the Galaxy and that the SN Ia progenitors have longer lifetimes than the progenitors of type II supernovae (SN II, resulting from exploding massive stars), which are the source of Galactic oxygen; Tinsley argued that the time delay between SN II and SN Ia, of at least 10^8 years, is responsible for the enhanced $[\text{O}/\text{Fe}]$ ¹ ratios observed in halo stars. Theoretical predictions of SN II element yields show that $[\alpha/\text{Fe}]$ (where α includes the elements O, Mg, Si, S, Ca, and Ti) increases with increasing progenitor mass (e.g. Woosley & Weaver 1995). In principle, the IMF of a stellar system could be inferred from the observed $[\alpha/\text{Fe}]$ ratios. Note that if a stellar system is found to have a high average metallicity, and an IMF skewed to high-mass stars is responsible for increasing the yield, then the composition should reflect an increased $[\alpha/\text{Fe}]$ ratio that is due to the increased $[\alpha/\text{Fe}]$ from high mass SN II. In fact, this idea was used by Matteucci & Brocato (1990) to explain the putative high metallicity of the Galactic bulge, with the prediction that $[\alpha/\text{Fe}]$ is enhanced in the bulge.

The $[\alpha/\text{Fe}]$ ratio is also sensitive to the SFR in Tinsley's model: If the SFR is high, then the gas will reach higher $[\text{Fe}/\text{H}]$ before the first SN Ia occur, and the position of the knee in the $[\alpha/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ diagram (Figure 1) will be at a higher $[\text{Fe}/\text{H}]$. Also, because the knee marks the time of the first SN Ia, then the formation time scale of a stellar system can be estimated by noting the fraction of stars with $[\text{Fe}/\text{H}]$ below this point.

Another potentially useful diagnostic of the $[\text{O}/\text{Fe}]$ ratio was pointed out by Wyse & Gilmore (1991): In a star-burst system, the O/Fe ratio of the gas is

¹ $[\text{A}/\text{B}]$ refers to an abundance ratio in $\log_{10}$ solar units, where A and B represent the number densities of two elements: $[\text{A}/\text{B}] = \log_{10}(\text{A}/\text{B})_{*} - \log_{10}(\text{A}/\text{B})_{\odot}$. Note that $\epsilon(\text{M}) = \log_{10}(\text{M}/\text{H})$.

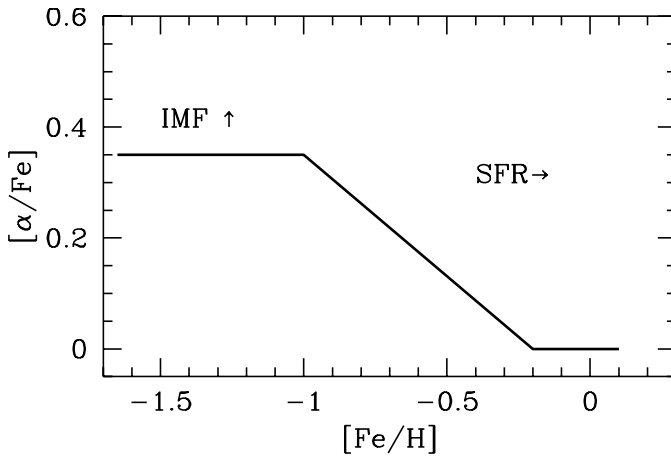


Figure 1 A schematic diagram of the trend of α -element abundance with metallicity. Increased initial mass function and star formation rate affect the trend in the directions indicated. The knee in the diagram is thought to be due to the onset of type Ia supernovae (SN Ia).

initially above solar owing to nucleosynthesis by SN II, but as time continues after the burst (with no new star formation) the SN II diminish, only SN Ia enrich the gas; ultimately subsolar $[O/Fe]$ ratios occur. Wyse & Gilmore (1991) claimed that the composition of the LMC is fit by this model.

Elements like C, O, and those in the iron-peak, thought to be produced in stars from the original hydrogen, are sometimes labeled as “primary.” The label “secondary” is reserved for elements thought to be produced from pre-existing seed nuclei, such as N and s-process heavy elements. The abundance of a primary element is expected to increase in proportion to the metallicity, thus $[M/Fe]$ is approximately constant. For a secondary element, $[M/Fe]$ is expected to increase linearly with $[Fe/H]$ because the yield is proportional to the abundance of preexisting seed nuclei. One difficulty is that N and the s-process elements (both secondary) do not show the expected dependence on metallicity.

THE SOLAR IRON ABUNDANCE

It is sobering, and somewhat embarrassing, that the solar iron abundance is in dispute at the level of 0.15 dex. This discrepancy comes in spite of the fact that more than 2000 solar iron lines, with reasonably accurate gf values, are available for abundance analysis; that the solar spectrum is measured with much higher S/N and dispersion than for any other star; that LTE corrections to Fe I abundance are small, at only +0.03 dex (Holweger et al 1991); and

that both theoretical and empirical solar model atmospheres are available, with parameters known more precisely than for any other star.

Anders & Grevesse (1989) reviewed published meteoritic and solar photospheric abundances for all available elements and found $\epsilon(\text{Fe}) = 7.51 \pm 0.01$ for meteorites and $\epsilon(\text{Fe}) = 7.67$ from the solar abundance analysis of Blackwell et al (1984, 1986), which was a notable increase from the earlier photospheric value of 7.50 ± 0.08 favored by Ross & Aller (1976). Blackwell et al's work utilized the Oxford group *gf* values for Fe I lines, which are known to be of high accuracy.

Pauls et al (1990) found $\epsilon(\text{Fe}) = 7.66$ from Fe II lines, but Holweger et al (1990), also using Fe II lines, found $\epsilon(\text{Fe}) = 7.48$. Biémont et al (1991) measured the solar iron abundance of 7.54 ± 0.03 with a larger sample of Fe II lines. Holweger et al (1991) found 7.50 ± 0.07 based on *gf* values for Fe I lines measured by Bard et al (1991).

Two recent papers are characteristic of the conflicting solar iron abundance: those by Holweger et al (1995) and Blackwell et al (1995). Blackwell et al (1995) employed Oxford *gf* values and the Holweger & Müller (1974) solar atmosphere and found $\epsilon(\text{Fe}) = 7.64 \pm 0.03$ from the Fe I lines; although the Fe II line results indicated $\epsilon(\text{Fe}) = 7.53$ dex.

When Blackwell et al (1995) computed iron abundances from the Kurucz (1992 unpublished) solar model, Fe I and Fe II lines gave better agreement, at 7.57 and 7.54 dex, respectively, but they claimed that the Kurucz model results are not valid because the solar limb darkening is not reproduced by the model. Blackwell et al (1995) concluded that neither the empirical Holweger-Müller model, nor the Kurucz theoretical model atmosphere, is adequate for measuring the solar iron abundance.

Holweger et al (1995) contested Blackwell et al's (1995) claim and argued that Fe I lines analyzed with the Holweger-Müller model give $\epsilon(\text{Fe}) = 7.48 \pm 0.05$, or 7.51 with the 0.03-dex non-local thermodynamic equilibrium (non-LTE) correction. Holweger et al (1995) found the same low solar iron abundance from both Fe I and Fe II lines in their analysis.

Lambert et al (1995a) found that the *gf* values of lines common to results of both Holweger et al (1995) and Blackwell et al (1995) had zero average difference, which suggests that *gf* values are not the source of the abundance difference. They attributed the difference mostly to variations in the measured equivalent widths and damping constants. Another low value of the solar iron abundance was found by Milford et al (1994), who found $\epsilon(\text{Fe}) = 7.54 \pm 0.05$ with the Holweger-Müller solar model and new *gf* values, from weak Fe I lines that are not sensitive to uncertainties in damping constants or microturbulent velocity.

Kostik et al (1996) attempted to resolve the differences between Blackwell et al (1995) and Holweger et al (1995). Kostik et al found that the Blackwell

et al's equivalent widths are systematically higher than Holweger et al's values; remeasurement by Kostik et al favored the Holweger et al values. Kostik et al also found suspicious trends in the gf values of the Holweger et al (1995) study, and they agree with Grevesse & Noels (1993) that the spread in iron abundance is dominated by uncertainties in the gf values. They also noted that uncertainties in the microturbulent velocity and collisional damping constants are extremely important to the adopted value. Kostik et al provide a best estimate of the solar iron abundance of 7.62 ± 0.04 , which favors the high solar iron abundance; although little weight was placed on the significance of this result.

Anstee et al (1997) measured the solar iron abundance from profile-matching 26 strong Fe I lines, using accurate laboratory collision-damping constants and gf values. They found $\epsilon(\text{Fe}) = 7.51 \pm 0.01$ in complete agreement with the meteoritic iron abundance of Anders & Grevesse (1989), independent of non-thermal motions in the photosphere. Anstee et al traced the discrepancies between previous studies to the use of different atomic data, measured equivalent widths, and assumed microturbulent velocity.

It now seems that the weight of the evidence favors the low value of the solar iron abundance, and the issue may finally be settled; however, this statement has been made before

SUPER METAL-RICH STARS

The existence of super metal-rich (SMR) stars was first claimed by Spinrad & Taylor (1969), based on low-resolution spectra. The term SMR is generally meant to signify that a star is more metal-rich than the sun by an amount that cannot be explained as simple measurement error. The existence of SMR stars is, historically, a controversial subject; the main question is whether SMR stars are really metal-rich or just appear so because of some kind of measurement dispersion or systematic error. Perhaps the notion of SMR stars became more acceptable with claims that the Galactic bulge red giant stars are on average more metal-rich than the sun (e.g. Whitford & Rich 1983, Frogel & Whitford 1987, Rich 1988). McWilliam & Rich (1994) showed that the average bulge $[\text{Fe}/\text{H}]$ is the same as in the solar neighborhood, but that the most metal-rich bulge giant, BW IV-167, at $[\text{Fe}/\text{H}] = +0.44$ is almost identical to μ Leo, a metal-rich disk giant. Taylor (1996) has reviewed abundance estimates for SMR stars, including low- and high-resolution results, and concluded that true SMR stars do not exist.

Given the controversy and the potential significance for chemical evolution, it seems important to establish whether any firm cases of SMR stars exist at all. In the Galactic disk, the most well-studied SMR candidate is the K giant star μ Leo. High-resolution high-S/N model atmosphere abundance analyses of μ

Leo have been performed by several groups: Gustafsson et al (1974), Branch et al (1978), Brown et al (1989), Gratton & Sneden (1990), McWilliam & Rich (1994), and Castro et al (1996) all found values near $[\text{Fe}/\text{H}] = +0.45$ for a solar scale of $\epsilon(\text{Fe}) = 7.52$; on the other hand, Lambert & Ries (1981), McWilliam (1990), and Luck & Challener (1995) found $[\text{Fe}/\text{H}]$ from $+0.1$ to $+0.2$ dex.

Metal-rich stars in the McWilliam (1990) study (e.g. μ Leo) were affected by two systematic problems: CN blanketing depressed most of the μ Leo continuum regions in the two small 100-Å portions of the spectrum observed (found by McWilliam & Rich 1994), which resulted in smaller equivalent widths; second, McWilliam (1990) did not have access to metal-rich model atmospheres, which caused underestimation of the $[\text{Fe}/\text{H}]$ for metal-rich stars (~ 0.1 -dex underestimate for μ Leo). Both of these effects decreased the measured μ Leo $[\text{Fe}/\text{H}]$ in the McWilliam (1990) work; accounting for the model atmosphere correction alone would increase $[\text{Fe}/\text{H}]$ to $+0.30$ dex.

The Luck & Challener (1995) study concluded that their sample of strong-lined stars showed only small iron abundance enhancements at $[\text{Fe}/\text{H}] \sim +0.1$ dex; in the case of μ Leo they found $[\text{Fe}/\text{H}] = +0.20$ dex. Luck & Challener (1995) chose not to use a SMR model atmosphere for μ Leo, thus artificially lowering the computed $[\text{Fe}/\text{H}]$ by ~ 0.08 dex (Castro et al 1996). Castro et al (1996) showed that the low Luck & Challener $[\text{Fe}/\text{H}]$ must result from differences in analysis because of the good agreement between equivalent widths of lines in common. Furthermore, Luck & Challener confused the $[\text{A}/\text{H}] = 0.0$ of the Bell et al (1976) atmosphere grid with a solar iron abundance of $\epsilon(\text{Fe}) = 7.67$ (from Anders & Grevesse 1989), whereas the models were actually calculated with $\epsilon(\text{Fe}) = 7.50$. Castro et al noted that when these two problems are taken into account the Luck & Challener result for μ Leo becomes $[\text{Fe}/\text{H}] = +0.43$, assuming the solar $\epsilon(\text{Fe}) = 7.52$.

Thus the most recent high resolution abundance studies of μ Leo that are discordant with the notion of $[\text{Fe}/\text{H}] = +0.45$ can be readily resolved, and it appears that there is a convergence of the μ Leo iron abundance near $[\text{Fe}/\text{H}] = +0.45$ dex with the assumed low value for the solar iron abundance. I do not have an explanation for the Lambert & Ries (1981) low $[\text{Fe}/\text{H}]$, although it seems possible that the heavy line blanketing and limited spectral coverage may have affected the continuum placement.

Studies with the highest S/N spectra, and the most detailed abundance analyses (e.g. Gratton & Sneden 1990, Branch et al 1978, Castro et al 1996, McWilliam & Rich 1994), consistently find $[\text{Fe}/\text{H}] \sim +0.4$ dex for μ Leo. In conclusion, the high dispersion abundance analyses confirm at least one case of super metallicity.

High-resolution abundance analyses of SMR stars have also been carried out by Edvardsson et al (1993), who found F dwarf stars up to $[\text{Fe}/\text{H}] = +0.26$

dex; Feltzing (1995), who extended the Edvardsson sample to find stars between $[\text{Fe}/\text{H}]$ of -0.08 and $+0.42$ dex; and Castro et al (1997), who studied a subset of the sample identified by Grenon (1989) and found $[\text{Fe}/\text{H}]$ ranging from $+0.10$ to $+0.50$ dex. McWilliam & Rich (1994) found two SMR Galactic bulge giants, BW IV-167 and BW IV-025, with $[\text{Fe}/\text{H}]$ of $+0.44$ and $+0.37$ dex, respectively. It appears that high-resolution abundance studies do find SMR stars with $[\text{Fe}/\text{H}]$ up to approximately 0.4 – 0.5 dex.

OBSERVED METALLICITY DISTRIBUTION FUNCTION

In this section, I discuss some implications and uses of the most basic chemical composition information, namely metallicity. The word metallicity has more than one meaning: The precise definition is that metallicity is the mass fraction of all elements heavier than helium, denoted by the symbol Z ; this is not always practical for observers because information usually does not exist for all elements. For observational stellar astronomy, metallicity is more often used to refer to the iron abundance. Unless explicitly stated the word metallicity used here refers to $[\text{Fe}/\text{H}]$, the logarithmic iron abundance relative to the solar value.

The Disk

Because the main-sequence lifetimes of G and F dwarfs are comparable to the age of the Galaxy, all the G dwarfs ever born are assumed to still exist (although see discussion of metallicity-dependent lifetimes by Bazan & Mathews 1990), and so these stars can provide a complete picture of Galactic chemical evolution. Early studies of the metallicity distribution of G dwarfs, within about 25 pc of the sun (vandenBergh 1962, Schmidt 1963, Pagel & Patchett 1975), showed that there is a deficit of metal-poor stars relative to the prediction of the Simple model; this is the well-known G-dwarf problem. The metallicities of these early studies were based on UV excesses (see Wallerstein & Carlson 1960, Sandage 1969), which are accurate to approximately $1\sigma = 0.25$ dex (Pagel & Patchett 1975); although Norris & Ryan (1989) claim uncertainties of ± 0.45 dex. The observed metallicity distributions contain biases that must be taken into account in order to obtain the true metallicity function (e.g. see Sommer-Larsen 1991 and Pagel 1989).

Many possible explanations were presented to account for the G-dwarf problem (e.g. Audouze & Tinsley 1976), but infall of metal-poor gas onto the disk was the most favored solution. To fit the observed metallicity function by this scheme, the original disk was at most 5% of the present disk mass (Pagel 1989), with mass infall occurring over several billion years. Variants of the Simple model exist that include gas infall in various ways (e.g. Larson 1974, 1976,

Lynden-Bell 1975, Clayton 1985, 1988, Pagel 1989). All of these models predict a strict age-metallicity relation (AMR) with no abundance dispersion.

In these models, the halo could not have been responsible for the bulk of the gas infall because the present-day luminous halo mass is only a few percent of the disk (Sandage 1987, Pagel 1989); a metallicity function of the disk+halo still suffers a paucity of metal-poor stars relative to the simple model (e.g. Worthey 1996). Tosi (1988) showed that infall of gas with metallicity $0.1 Z_{\odot}$ provides as effective an explanation of the observed disk metallicity distribution function as infall of zero metallicity gas; however, infalling gas with $Z = 0.4 Z_{\odot}$ is excluded by observations.

A number of studies over the last decade and a half have combined star count and kinematic information with metallicities estimated from UV excesses (e.g. Sandage & Fouts 1987), *ubvy* β photometry (e.g. Nissen & Schuster 1991), and low S/N spectra (e.g. Carney et al 1987, Jones et al 1995). The assembled databases have been used to imply the existence of various Galactic populations. For example, the thick disk of Gilmore & Reid (1983) is characterized by scale height of ~ 1.3 pc, mean $[\text{Fe}/\text{H}] \sim -0.6$ dex, and dispersion 0.3 dex (Gilmore & Reid 1983, Gilmore 1984, Gilmore & Wyse 1985, Wyse & Gilmore 1986), with no apparent metallicity gradient. Wyse & Gilmore (1995) conclude that the data are best fit by overlapping thick and thin disks; the thick disk has a mean metallicity of $[\text{Fe}/\text{H}] \sim -0.7$ dex, ranging from -0.2 to -1.4 dex. A low metallicity tail, extending down to $[\text{Fe}/\text{H}] \sim -2$ to -3 , was claimed by Norris & Ryan (1991), Beers & Sommer-Larsen (1995), and Pagel & Tautvaisiene (1995). Typical star count models yield thick disk to thin disk ratios of a few percent (e.g. Majewski 1993). The thin disk metallicity peaks near $[\text{Fe}/\text{H}] = -0.25$ dex, ranging from $+0.2$ to -0.8 dex (Wyse & Gilmore 1995).

The Halo

The Galactic halo does not appear to suffer from a severe G-dwarf problem (Laird et al 1988, Pagel 1989, Beers et al 1992). The halo metallicity ranges from -4 dex to just below the solar value, with a mean of ~ -1.6 (Laird 1988, Hartwick 1976); Hartwick (1976) noted that this low metallicity suggested that either the halo yield was much lower than in the disk or that gas was removed from halo star formation (e.g. Ostriker & Thuan 1975). The favored model is that the halo lost its gas before chemical evolution could go to completion. Carney et al (1990) and Wyse & Gilmore (1992) suggested that the missing spheroid mass fell to the center of the Galaxy and contributed most of the bulge mass, based on angular momentum considerations.

Whether or not there is a minimum metallicity level, below which stars do not exist, has been debated for at least 20 years. Hartquist & Cameron (1977) predicted that there was an era of “pregalactic nucleosynthesis” by very massive

zero metallicity objects; as a result, the Galactic halo would have formed with a non-zero metal content.

Bond (1981) and Cayrel (1987) claimed that there is a paucity of stars below $[\text{Fe}/\text{H}] \sim -3$ relative to a Simple one-zone model of chemical evolution; this was attributed to a reduced efficiency of forming low-mass stars at low metallicity. Indeed several theoretical investigations (e.g. Kahn 1974, Wolfire & Cassinelli 1987, Yoshii & Saio 1986, and Uehara 1996) have predicted that at low metallicity the IMF is skewed to high-mass stars. Contrary to Bond's suggestion, the huge increase in the number of known metal-poor halo stars (e.g. Beers et al 1985, 1992) led to agreement between the observed metallicity function and predictions from modified Simple models (Beers et al 1985, 1992, Laird et al 1988, Ryan & Norris 1991) down to the lowest measurable abundance, consistent with no metallicity dependence of the IMF.

Audouze & Silk (1995) claimed that there is a lower limit to the metallicity that can form stars, based on predictions concerning the amount of material that can dilute and cool SN ejecta; they estimated the lower limit to be approximately $[\text{Fe}/\text{H}] \sim -4$.

The most metal-poor star presently known is CD -38 245, at $[\text{Fe}/\text{H}] = -4.01$ (McWilliam et al 1995a,b), although it only narrowly beats CS 22949-037 for the record, at $[\text{Fe}/\text{H}] = -3.99$. This iron abundance for CD -38 245 is supported by Gratton & Sneden (1988), who found $[\text{Fe}/\text{H}] = -3.97$, but it is higher than the metallicity of Bessell & Norris (1984), who found $[\text{Fe}/\text{H}] = -4.5$. Norris et al (1993) also analyzed stars from the list of Beers et al (1992), one of which was CS 22885-096, with a measured $[\text{Fe}/\text{H}] = -4.24$. McWilliam et al (1995a) found $[\text{Fe}/\text{H}] = -3.79$ for this star and explained the difference as due to systematic analysis effects of 0.4 dex; if applied to the Bessell & Norris (1984) result, the same zero point would bring all three analyses into agreement at $[\text{Fe}/\text{H}] = -4.0$ for CD -38 245.

Thus, despite the heroic effort by George Preston of searching for metal-poor stars by visually inspecting over one million objective prism spectra (Beers et al 1985), the honor of the most metal-poor star known in the Galaxy still belongs to CD -38 245.

The Bulge

Measurement of the metallicity of Galactic bulge stars has been somewhat controversial in the last 15 years. Early bulge metallicity studies focused on stars in Baade's window, at Galactic latitude -4° . Initial low-resolution studies of 21 bulge giants by Whitford & Rich (1983) suggested that most of the bulge stars are super metal-rich.

Frogel & Whitford (1987) amassed photometric and spectral-type data for a large number of bulge giants. They found that bulge M giants have stronger TiO

and CO bands than solar neighborhood M giants consistent with a metal-rich bulge.

Rich (1988) measured low-resolution indices of strong lines (Mg *b* and Fraunhofer Fe I lines) in 88 bulge giants in Baade's window and several bright standards. Calibration of the indices suggested a range of $[\text{Fe}/\text{H}]$, from -1.0 to $+0.8$ dex for the bulge, with a mean value twice the solar value.

Terndrup et al (1991) found a mean bulge metallicity of $+0.3$ dex for M giant stars in Baade's Window, based on $R=1000$ spectrophotometry, which confirmed earlier results.

Geisler & Friel (1992) used Washington photometry to measure the metallicity of 314 red giants in the Galactic bulge, through Baade's window. They found the mean $[\text{Fe}/\text{H}] = +0.17 \pm 0.15$ dex, in good agreement with Rich (1988). They also found a high frequency of metal-poor stars, consistent with that expected from a simple closed box model, as found by Rich (1990).

Rich (1990) showed that the Galactic bulge contains a higher frequency of metal-poor stars than the solar neighborhood. In fact, the bulge metallicity function does not exhibit the G-dwarf problem. This is perhaps somewhat surprising because the bulge must be the final repository of infalling material (for example, the Sagittarius dwarf found by Ibata et al 1994). It may be that most of the infall occurred very rapidly, or that material that fell into the bulge, such as a dwarf galaxy, was stripped of its gas before reaching the bulge.

With the apparent convergence of different methods used to measure the bulge metallicity, it was a surprise that the first high-dispersion model atmosphere abundance analysis of bulge stars (McWilliam & Rich 1994) found that the bulge is slightly iron-poor relative to the solar neighborhood. McWilliam & Rich (1994) computed $[\text{Fe}/\text{H}]$ for 11 bulge red giants, covering the full metallicity range, which had previously been measured by Rich (1988). A correlation of $[\text{Fe}/\text{H}]$ values of McWilliam & Rich (1994) with those of Rich (1988) showed that Rich (1988) systematically overestimated the $[\text{Fe}/\text{H}]$ of the most metal-rich stars. A regression relation between McWilliam & Rich's (1994) and Rich's (1988) $[\text{Fe}/\text{H}]$ results was used to compute corrected $[\text{Fe}/\text{H}]$ (Rich 1988) for the full sample of 88 stars. Rich's (1988) $[\text{Fe}/\text{H}]$ values corrected in this way have a mean of -0.25 dex, slightly below the mean value of -0.17 dex for solar neighborhood red giants (McWilliam 1990). The corrected bulge metallicity function still shows the excess of metal-poor stars relative to the solar neighborhood noted by Rich (1990). McWilliam & Rich (1994) also found unusually high $[\text{Mg}/\text{Fe}]$ and $[\text{Ti}/\text{Fe}]$ ratios in the bulge stars, which might explain why previous investigators found high average metallicities.

Subsequent model atmosphere abundance analyses of two stars in the McWilliam & Rich (1994) sample (Castro et al 1996; A McWilliam, RC Peterson, DM Terndrup & RM Rich, in preparation) confirmed the McWilliam

& Rich (1994) [Fe/H] results. The low [Fe/H] of bulge stars in Baade's window found by McWilliam & Rich (1994) was supported by later low-resolution studies; for example, the analysis of low-resolution spectra of 400 bulge giants by Terndrup et al (1995) and Sadler et al (1996) found a low mean [Fe/H] ~ -0.1 dex.

AGE-METALLICITY RELATION

The existence of an age-metallicity relation (AMR) in the disk is an important issue for developing chemical evolution models. There is currently some uncertainty whether an AMR exists: Studies of open cluster metallicities and ages (e.g. Arp 1962, Geisler 1987, Geisler et al 1992, Friel & Janes 1993) have resulted in the conclusion by some that there is no AMR in the Galactic disk (see the review by Friel 1995). The main factor in determining open cluster metallicity appears to be galactocentric radius (e.g. Geisler et al 1992). It is also clear that there is a large scatter in metallicity at any given age in the disk: The dispersion in the age-metallicity diagram is exemplified by the presence of very old open clusters with metallicities near or above the solar value. The open cluster NGC 188 has historically been used to illustrate this point (e.g. Eggen & Sandage 1969); but the most clear-cut modern case is NGC 6791, which is more metal-rich than the sun, with [Fe/H] $\sim +0.2$ to $+0.3$ dex (Peterson & Greene 1995, Montgomery et al 1994), but very old at $\sim 10 \times 10^9$ years (Montgomery et al 1994, Tripicco et al 1995).

The conclusion against an AMR is at odds with claims based on studies of field stars. For example, Twarog (1980), Meusinger et al (1991), and J nch-S rensen (1995) all employed *uvby* β photometry and found a trend of decreasing metallicity with increasing stellar age. Edvardsson et al (1993) used spectroscopic abundance analysis to determine [Fe/H] and *uvby* β photometry for the ages. They found an AMR consistent with the results of Twarog (1980) and Meusinger et al (1991) but with a considerable scatter about the mean trend (Figure 2). The J nch-S rensen data indicated a similar AMR slope and scatter as Edvardsson et al's data. The age-metallicity diagram from these studies (e.g. Figure 2) show a lower envelope to the observed metallicity of stars that increases with Galactic time; in particular, no young stars with [Fe/H] ~ -1 have been found in the solar neighborhood (although low metallicity stars at large galactocentric radii are known; e.g. Geisler 1987, Geisler et al 1992).

The large scatter in metallicity at all ages is the one consistent conclusion common to the age-metallicity diagrams for both the field stars and open clusters. Fran ois & Matteucci (1993) suggested that the scatter could be due to orbital diffusion; however, Edvardsson et al (1993) showed that this is not enough to reduce the observed scatter in the age-metallicity diagram.

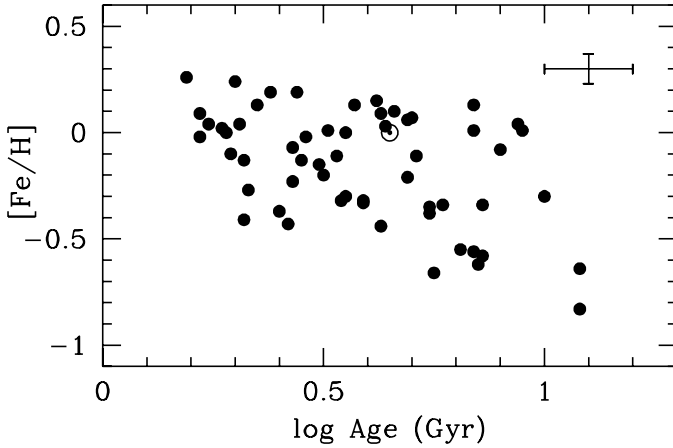


Figure 2 The age-metallicity relation for the solar neighborhood, from the data of Edvardsson et al (1993). The sample is limited to galactocentric radius $7.7 \leq R_m \leq 9.3$ kpc, maximum height above the plane $Z_{max} \leq 0.26$ kpc, and eccentricity $e \leq 0.16$. The position of the Sun is indicated.

It is clear that certain biases occur in samples of field stars that could conspire to create an apparent AMR, even if none exists (Knude 1990, Grenon 1987); indeed, Friel (1995) states that the age-metallicity trends seen by Twarog (1980) are the result of these selection effects. However, Twarog was aware of the selection biases and pointedly went to great effort to avoid them. Jønch-Sørensen (1995) estimated an upper limit to the number of metal-poor young stars and claimed that the selection bias against metal-poor young stars could not account for the apparent AMR. Edvardsson et al (1993) made a correction for a metallicity bias, but the AMR was still present. Obviously a definitive resolution to the existence or absence of a mean AMR in field stars would be extremely valuable. If age and metallicity data for the halo are added to Figure 2, as done by Eggen & Sandage (1969), a strong AMR would result; however, the validity of combining these two populations is not certain.

The large range of metallicities present for all ages suggests that chemical enrichment up to solar metallicity can occur on rapid time scales ($\sim 1 \times 10^9$ years) and that the disk has been chemically inhomogeneous throughout its development. The dispersion in the AMR at the solar circle (as seen in the Edvardsson et al 1993 study) shows that the composition of the Galactic disk did not evolve homogeneously. Traditional chemical evolution models, for example those of Lynden-Bell (1975), Larson (1976), Matteucci & François (1989), Pagel (1989), Sommer-Larsen (1991), and Pagel & Tautvaisiene (1995), cannot account for the observed AMR dispersion because they all assume instantaneous

mixing of recycled gas and a homogeneous steady infall; as a consequence chemical homogeneity is preserved at all times.

Reeves (1972) suggested that significant spatial inhomogeneities in elemental abundances could occur as a result of self-enrichment of star-forming regions by SN events. However, Edmunds (1975) investigated this possibility and concluded that the Galactic disk is well mixed. White & Audouze (1983) developed analytical expressions that extended the standard chemical evolution model of Lynden-Bell (1975) to the case of inhomogeneous steady-state evolution. Two important mixing parameters dictated the inhomogeneity: (a) the mean mass of disk material mixed with a unit mass of enriched material from star formation events and (b) the mean mass of disk material mixed with a unit mass of infalling gas.

Recent models of Galactic evolution attempted to describe inhomogeneous chemical evolution: Pilyugin & Edmunds (1996a,b) and Raiteri et al (1996). Both studies adopt the Twarog (1980) AMR and the dispersion about this relation indicated by Edvardsson et al (1993).

Pilyugin & Edmunds (1996b) considered inhomogeneity by two mechanisms. In the first approach, self-enrichment of gas in star forming regions (H II regions) for 3×10^7 years is permitted, after which time the gas is instantaneously mixed with the ambient disk gas. This approximates a star-forming region in which SN ejecta enrich the region with metals until the energy input from SN is sufficient to disrupt the cloud in 3×10^7 years, followed by mixing with the disk in $\sim 10^8$ years. Justification for this assumption comes from Cunha & Lambert (1992, 1994), who showed that self enrichment in the Orion association has occurred in $\sim 80 \times 10^6$ years, based on enhancements in O and Si abundances as a function of age of the Orion subgroups.

Self enrichment of the H II regions gave a satisfactory fit to the dispersion in the oxygen abundance with time, but it was incapable of reproducing the observed dispersion in Fe abundance. The difficulty in reproducing the Fe dispersion was caused by the fact that Fe is produced mainly in SN Ia, whose progenitor lifetimes are thought to be $\sim 1 \times 10^9$ years, well in excess of the self-enrichment time scale. Pilyugin & Edmunds (1996b) suggest that self-enrichment of H II regions results in larger dispersion for oxygen abundances (SN II progenitors with short lifetimes) than iron abundances versus age. They concluded that the large observed dispersion for both O and Fe implicates another source of inhomogeneity.

Pilyugin & Edmunds (1996b) suggested that episodic gas infall could account for the large dispersions in the AMR for both Fe and O. If infalling gas fell onto the disk in a nonuniform fashion (both temporally and spatially), then disk gas could reach solar metallicity followed by substantial dilution to lower metallicities. Stars formed over such a cycle would exhibit equal Fe and O

dispersion in the AMR because dilution affects all species equally. If this is the case, then the infalling gas cannot be pure hydrogen; otherwise the dilution would preserve solar abundance ratios even near $[\text{Fe}/\text{H}] = -1$, which is not observed. The gas would need to be of halo composition, with $[\text{Fe}/\text{H}] \sim -1$, to avoid the problem of solar ratios in low metallicity disk stars.

Raiteri et al (1996) have developed N -body/hydrodynamical simulations of Galactic chemical evolution. The method seems very promising and does produce an AMR similar to Twarog's (1980) with a large metallicity dispersion; it also predicts significant dispersion in the $[\text{O}/\text{Fe}]$ ratio at all metallicities, which provides a basis for testing the model. There are some problems, however, such as a very high frequency of low metallicity stars.

ABUNDANCE TRENDS WITH METALLICITY

Alpha Elements

Enhancements of α elements in metal-poor stars were first identified by Aller & Greenstein (1960) and more firmly established by Wallerstein (1962), who found excesses of Mg, Si, Ca, and Ti relative to Fe. A corresponding enhancement for oxygen was first discovered by Conti et al (1967). The work of Clegg et al (1981) and François (1987, 1988) showed that S is also overabundant in metal-poor stars. These enhancements increase linearly with decreasing metallicity, reaching a factor of two above the solar $[\alpha/\text{Fe}]$ ratios at $[\text{Fe}/\text{H}]$ near -1 ; below $[\text{Fe}/\text{H}] = -1$ the enhancements are approximately constant. Figure 3a shows the general trend of $[\text{O}/\text{Fe}]$ with $[\text{Fe}/\text{H}]$. It is important to emphasize that " α element" is simply a convenient phrase used to signify the observation that some even- Z elements (O, Mg, Si, S, Ca, and Ti) are overabundant relative to iron at low metallicity, and it does not signify that these are all products of a single nuclear reaction chain that occurs in the same astrophysical environment.

As mentioned in the introduction Tinsley (1979) suggested that the $[\alpha/\text{Fe}]$ trend with $[\text{Fe}/\text{H}]$ is due to the time delay between SN II, which produce α elements and iron-peak elements (e.g. Arnett 1978, Woosley & Weaver 1995), and SN Ia, which yield mostly iron-peak with little α element production (e.g. Nomoto et al 1984, Thielmann et al 1986). Thus, after the delay for the onset of SN Ia, the $[\alpha/\text{Fe}]$ ratio declines from the SN II value. The SN Ia time scale is an important consideration for this model. Iben & Tutukov (1984) favor a mechanism with mass transfer during the merging of a CO+CO white dwarf binary system; time scales for SN Ia from this model range from 10^8 to 10^{10} years, depending on progenitor masses and mass transfer parameters. Smecker-Hane & Wyse (1992) obtained estimates for the first SN Ia of 10^8 years.

Other explanations for the α -element trend have been put forward: Maeder (1991) suggested that exploding Wolf-Rayet stars (type Ib supernovae, SN Ib)

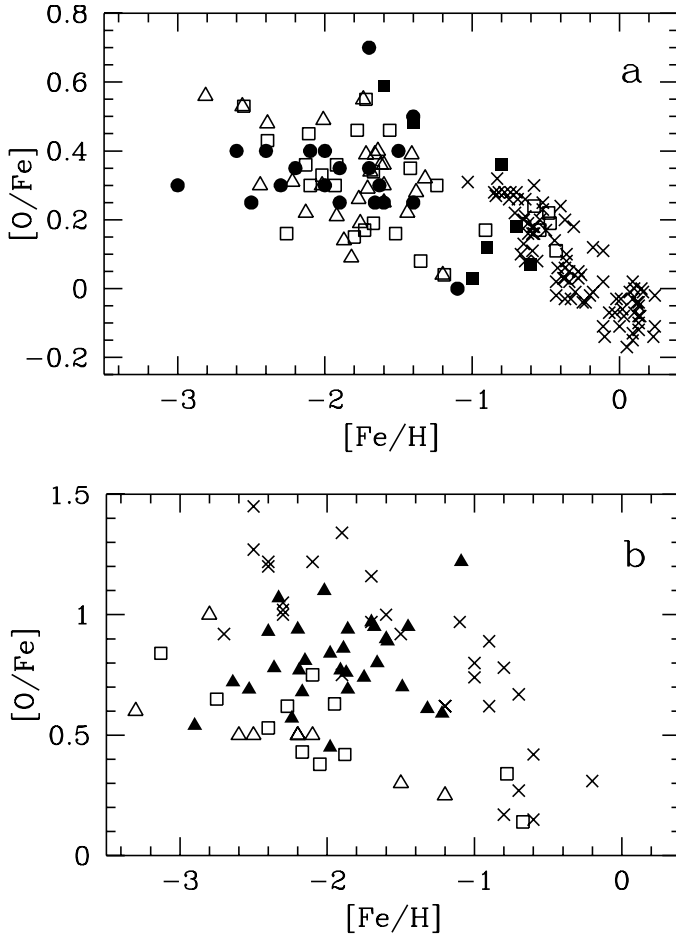


Figure 3 The trend of oxygen abundance with metallicity. The favored trend is shown in (a), a compilation of [O I] results: crosses from disk data of Edvardsson et al (1993), filled squares from Spite & Spite (1991), filled circles from Barbuy (1988), open triangles from Kraft et al (1992) and Sneden et al (1991), open squares from Shetrone (1996a). (b) shows results from the O I triplet: crosses (Abia & Rebolo 1989) and filled triangles (Tomkin et al 1992); low S/N results from ultraviolet OH lines are indicated by open squares (Nissen et al 1994) and open triangles (Bessell et al 1991). Note the difference in the scale of the ordinate between (a) and (b).

might be responsible for the observed α -element abundance trend. Wolf-Rayet stars are the bare cores of massive stars that have lost their outer envelopes through copious stellar winds. The radiatively driven winds are metallicity-dependent, producing significant numbers of Wolf-Rayet stars above $[\text{Fe}/\text{H}] \sim -1$. The chemical yields depend on the mass-loss rates: At high metallicity the strong winds remove much of the helium before it is further transformed into heavy elements.

Edmunds et al (1991) suggested that metallicity-dependent element yields could be the source of the α -element abundance trend and predicted that SMR stars should possess subsolar $[\alpha/\text{Fe}]$ ratios. The theoretical element yields from SN II (e.g. Woosley & Weaver 1995) do not show such a metallicity dependence; however, some star formation theories have predicted a metallicity-dependent IMF (e.g. Kahn 1974, Yoshii & Saio 1986), which might conceivably result in a steady increase of the SN Ia/SN II ratio with increasing metallicity and thereby account for the observed α -element trend.

Disk Alpha Elements

Studies of disk dwarf stars by several workers (e.g. Clegg et al 1981, Tomkin et al 1985, François 1986, Gratton & Sneden 1987, Edvardsson et al 1993) confirmed the trend of increasing $[\alpha/\text{Fe}]$ with decreasing $[\text{Fe}/\text{H}]$ in the Galactic disk, as established by the analysis of G dwarfs by Wallerstein (1962); typically $[\alpha/\text{Fe}] \sim +0.4$ at $[\text{Fe}/\text{H}] \sim -1.0$. The data of Tomkin et al (1986) and Edvardsson et al (1993) show that for Mg, Ca, and Si, there is a plateau at $[\alpha/\text{Fe}] = 0.0$ above $[\text{Fe}/\text{H}] \sim -0.2$ dex (see Figure 3a). This plateau suggests a transition from one kind of chemical evolution environment to another, which is consistent with the idea that above $[\text{Fe}/\text{H}] = -0.2$, the ratio of SN Ia/SN II had reached a constant value.

Edvardsson et al (1993) found that when the disk stars are separated into bins of mean galactocentric radius, R_m , the α -element enhancements are seen to be maintained to higher $[\text{Fe}/\text{H}]$ at small R_m (see Figure 4). In Tinsley's picture of SN Ia and SN II this suggests that enrichment by SN II occurred to higher $[\text{Fe}/\text{H}]$ in the inner disk than in the outer disk, before the first SN Ia occurred, in agreement with models of the disk that predict higher SFR in the inner disk than in the outer regions (e.g. Larson 1976, Matteucci & François 1989). Edvardsson et al's results also indicate that at the solar circle, old stars seem to show a distinctly different $[\alpha/\text{Fe}]$ trend than young stars, and this suggests that the SFR increased with time in the disk. There is a hint that the inner disk stars of the Edvardsson et al sample show a bimodal $[\alpha/\text{Fe}]$ ratio, rather than a slope with $[\text{Fe}/\text{H}]$.

In order to reduce scatter in the trend with metallicity, α -element abundances have often been averaged; Lambert's (1987) review popularized the mean relation between $[\alpha/\text{Fe}]$ and $[\text{Fe}/\text{H}]$. The work of Edvardsson et al (1993) indicated

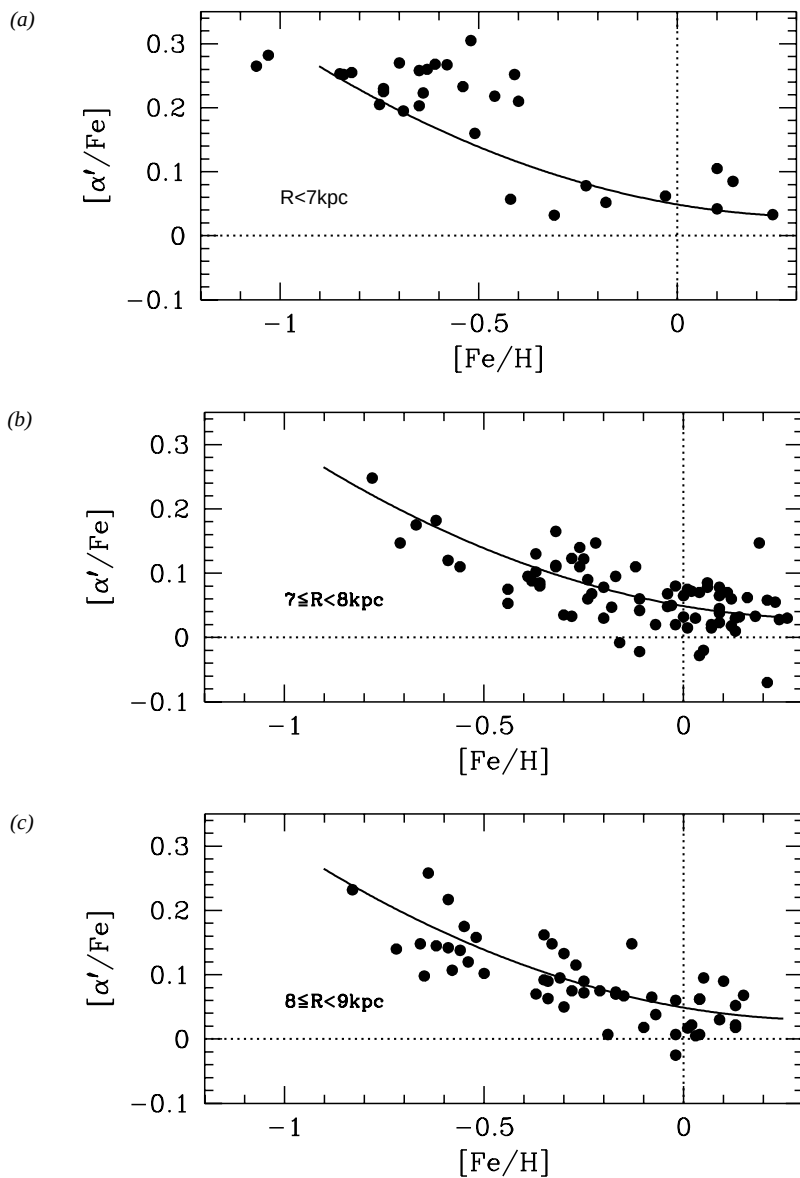


Figure 4 (continued)

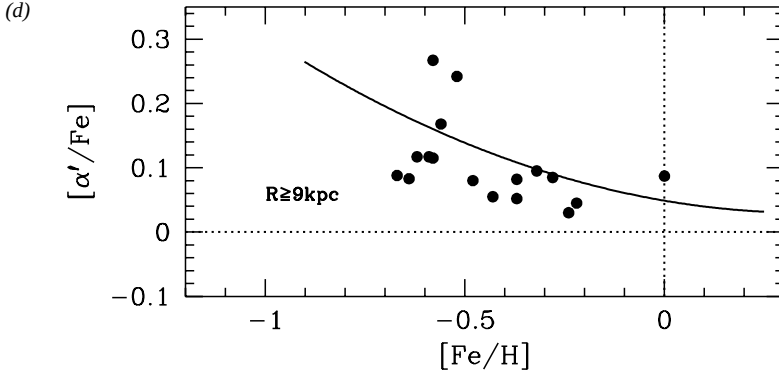


Figure 4 The run of $[\alpha'/\text{Fe}]$, computed from $[(\text{Mg}+\text{Si}+\text{Ca}+\text{Ti})/\text{Fe}]$, versus iron abundance for four ranges in galactocentric radius, from the data of Edvardsson et al (1993). In the inner disk, $R_m \leq 7$ kpc, $[\alpha'/\text{Fe}]$ is higher than the mean trend (indicated by the solid line), while the outer disk shows an $[\alpha'/\text{Fe}]$ deficiency. The trends at large and small R_m seem to show a bimodal appearance, rather than the shift indicated in Figure 1 for different SFR.

that the trends are not the same for all α elements: Ca and Si abundances correlate very well, but both Mg and Ti are systematically over-enhanced relative to Ca and Si. These observations of subtle α -element trends in the disk stars are similar to, but less extreme than, the enhanced Mg and Ti abundances found for Galactic bulge stars by McWilliam & Rich (1994). Nissen & Edvardsson (1992) found a somewhat steeper decline in $[\text{O}/\text{Fe}]$ with $[\text{Fe}/\text{H}]$ than other α elements from Edvardsson et al (1993). If these differences within the α element family withstand further scrutiny it shows that the α elements are not made in a single process but are produced in different amounts by different SN.

Cunha & Lambert (1992, 1994) studied the chemical composition of B stars in various subgroups of the Orion association ($[\text{Fe}/\text{H}] \sim -0.05$) and found evidence for self-contamination of the association by nucleosynthesis products from SN II. In particular the subgroups show an abundance spread of ~ 0.3 dex for O, correlated with Si abundance, but no dispersion larger than the measurement uncertainties could be found for Fe, C, and N. This pattern of abundance enhancement is consistent with self-enrichment of the gas by SN II only. Additional support for this idea includes the spatial correlation of the O-Si-rich stars and the fact that the most O-Si-rich stars are found only in the youngest subgroup of the association. The time lag between the oldest and youngest subgroups is $\sim 11 \times 10^6$ years (Blaauw 1991), which is comparable to the lifetime of the massive stars. Thus, the massive stars had enough time to explode as SN and enrich the molecular cloud, but the time scale was too short

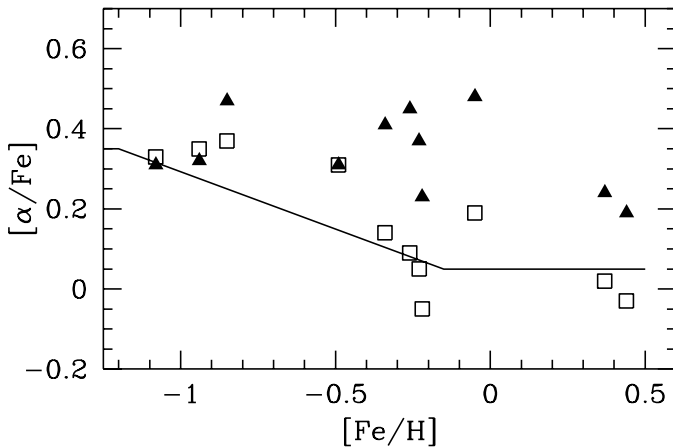


Figure 5 Trends of α -element abundances in the Galactic bulge, from McWilliam & Rich (1994). Filled triangles indicate the average $[(\text{Mg}+\text{Ti})/\text{Fe}]$ and open boxes indicate the average $[(\text{Si}+\text{Ca})/\text{Fe}]$. For Si and Ca the trends follow the solar neighborhood relation (solid line), whereas the Mg and Ti abundances are enhanced by ~ 0.4 dex for most stars, similar to the halo values.

to permit any pollution by SN Ia. If the same enrichment observed by Cunha & Lambert (1994) occurred in a similar cloud of zero-metal gas, the metallicity of the final generation would be approximately $[\text{Fe}/\text{H}] = -0.8$ dex.

As demonstrated by Cunha & Lambert (1992, 1994), chemical abundance studies of star-forming regions are a particularly useful way to study basic processes in chemical evolution and SN nucleosynthesis.

Bulge Alpha Elements

To date, the only extant detailed abundance analyses of α elements for Galactic bulge stars are by McWilliam & Rich (1994) and A McWilliam, A Tomaney & RM Rich (in preparation). McWilliam & Rich (1994) found that Mg and Ti are enhanced by $\sim +0.4$ dex in almost all bulge stars, even at solar $[\text{Fe}/\text{H}]$; however, the abundances of Ca and Si appear to follow the normal trend of α/Fe ratio with $[\text{Fe}/\text{H}]$ (see Figure 5).

Some overlap exists between the chemical properties of the McWilliam & Rich (1994) bulge giant sample and the disk F dwarfs of Edvardsson et al (1993): In general, the disk results (Edvardsson et al 1993) show that Mg and Ti are slightly enhanced relative to Si and Ca, which is similar to, but less extreme than, the $+0.4$ -dex enhancements of Mg and Ti in the bulge. Edvardsson et al (1993) identified a subgroup of stars with 0.1-dex enhancements of Na, Mg, and Al; these are conceivably related to the bulge giants, which have large Mg and

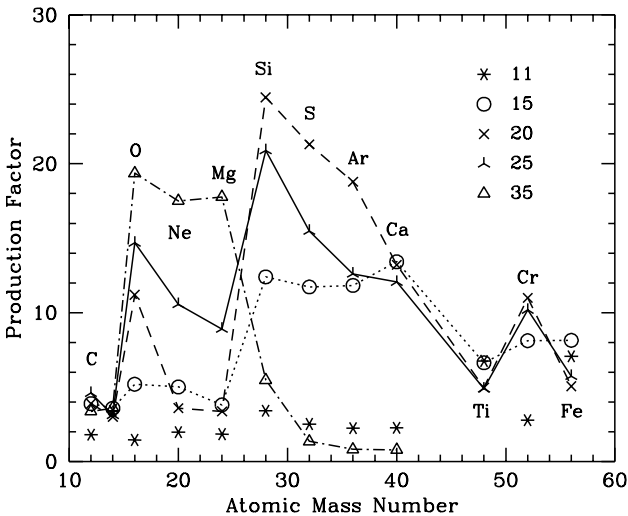


Figure 6 Production factors from models of SN II by Woosley & Weaver (1995). Ejected element abundances for various progenitor masses are indicated by *connected symbols*; O and Mg are produced in large quantities at high mass ($\sim 35 M_{\odot}$) but not in the lower mass ($15\text{--}25 M_{\odot}$) SN, which are responsible for most of the Si and Ca production. None of the models give significant enhancements of Ti relative to Fe, contrary to observations of stars in the Galactic bulge and halo. Note that production factor is defined as the ratio of the mass fraction of an isotope in the SN ejecta, divided by its corresponding mass fraction in the Sun. The mass of the progenitor making the indicated elements is given in the key in the upper right.

Al enhancements. The bulge [O/Fe] ratio is not well constrained: The extant data are insufficient to determine whether oxygen behaves like Mg and Ti or Si and Ca. However, any oxygen enhancement in the bulge must be less than $+0.5$ dex (A McWilliam, A Tomaney & RM Rich, in preparation).

The unusual mixture of α -element abundances in the bulge is evidence that α elements are made in different proportions by different SN; i.e. there are different flavors of SN with different α -element yields. This conclusion is borne out by predicted α -element yields (e.g. Woosley & Weaver 1995), as shown in Figure 6. Figure 6 illustrates that enhanced Mg could occur with relatively more $35 M_{\odot}$ SN progenitors than in the disk. The enhanced Ti is not explained by any SN nucleosynthesis predictions.

The Ti enhancements seen in bulge stars present a nice qualitative explanation for the well-known phenomenon that the spectral type of bulge M giants is later than disk M giants with the same temperature. Frogel & Whitford (1987) suggested that the later spectral types were due to overall super-metallicity of the bulge stars; McWilliam & Rich (1994) argued that the Ti enhancements

are sufficient to create the stronger bulge M giant TiO bands, without affecting overall metallicity. The enhanced Mg abundances may also explain Rich's (1988) high $[\text{Fe}/\text{H}]$ results, which were based on measurements of the Mg *b* lines and assumed that the bulge giants have the solar $[\text{Mg}/\text{Fe}]$ ratio.

Unfortunately, the unusual mixture of α -element abundances for the bulge makes it difficult to use these elements to estimate the bulge formation time scale; the simple picture of SN Ia and SN II implies a different time scale depending on which elements are considered. However, the observed Mg overabundances agree with the predictions of Matteucci & Brocato (1990) and a rapid formation time scale for the bulge.

Terndrup et al (1995) and Sadler et al (1996) analyzed low-resolution spectra of 400 bulge giants and found the average $[\text{Fe}/\text{H}] \sim -0.11$ dex, consistent with the result of McWilliam & Rich (1994). The $[\text{Mg}/\text{Fe}]$ ratios $+0.3$ dex and $+0.11$ dex respectively.

Multi-population synthesis analysis of low-resolution integrated light spectra of the Galactic bulge by Idiart et al (1996a) indicated a mean bulge abundance ratio of $[\text{Mg}/\text{Fe}] = +0.45$ dex. Using the same technique for elliptical galaxies and bulges of external spirals, Idiart et al (1996b) showed a general Mg enhancement of $\sim +0.5$ dex. Worthey et al (1992), using single-population models, analyzed spectra of giant elliptical galaxies and found Mg enhancements relative to Fe between $+0.2$ to $+0.3$ dex. These results provide supporting evidence in favor of enhanced Mg in the bulge, as claimed by McWilliam & Rich (1994). An obvious question arising from the population synthesis results is whether Ti is enhanced in external bulges and elliptical galaxies.

The abundance results for α elements in the bulge show that chemical abundance ratios are a function of environmental parameters. In this regard, further study of the detailed chemical composition of Galactic components will lead to an understanding of how environment affects chemical evolution, which can be used to interpret low-resolution low-S/N spectra of distant galaxies. In particular, it is necessary to check the McWilliam & Rich (1994) results for O, Ca, and Si because results for these three elements are less reliable than for Mg and Ti.

Halo Alpha Elements

The enhancement of α elements in the halo has been confirmed by numerous studies, both in the field and the globular cluster system (e.g. Clegg et al 1981, Barbuy et al 1985, Luck & Bond 1985, François 1987, 1988, Gratton & Snenen 1988, 1991, Zhao & Magain 1990, Nissen et al 1994, Fuhrmann et al 1995, McWilliam et al 1995a,b).

Because α -element yields are predicted to increase with increasing SN II progenitor mass (e.g. Woosley & Weaver 1995), the $[\alpha/\text{Fe}]$ ratio is sensitive to

the IMF. Therefore it is interesting to know if the $[\alpha/\text{Fe}]$ ratios in the halo are constant with changing $[\text{Fe}/\text{H}]$, if there is a slope to the $[\alpha/\text{Fe}]$ correlation with $[\text{Fe}/\text{H}]$, or if there is a measurable dispersion at a given $[\text{Fe}/\text{H}]$, which might indicate a change in the IMF.

Abundance studies of oxygen are frequently based on the weak [O I] forbidden lines at 6300 and 6363 Å for cool giants (e.g. Barbuy 1988) and the high excitation O I triplet lines at 7774 and 9263 Å for main-sequence stars (e.g. Tomkin et al 1992). Unfortunately, the O I lines have very high excitation potential, and the resulting abundances may be very sensitive to temperature uncertainties and non-LTE effects. Tomkin et al (1992) found $[\text{O}/\text{Fe}] \sim +0.8$ dex from the O I lines, with non-LTE calculations; but the strong temperature dependence suggests that oxygen abundances derived from the triplet lines are unreliable. On the other hand, the [O I] lines are very weak and frequently only the 6300-Å line can be measured; however, the [O I] results are considered more reliable than those from the O I lines because neither temperature or non-LTE effects are a problem. Recent oxygen abundances have been determined from OH lines in the UV by Bessell et al (1991) and Nissen et al (1994), whereas Balachandran & Carney (1996) used near-infrared OH lines. Both methods offer the advantage that many lines can be measured without severe non-LTE problems; but the reduced flux in the UV result in lower S/N and less reliable results for the UV OH lines than for the near-infrared OH lines.

All of these methods provide information on the free oxygen (uncombined into molecules) in the stellar atmospheres. However, for the total oxygen abundance, carbon abundances must also be known in order to account for the oxygen atoms locked up in the CO molecule.

The scatter in measured $[\text{O}/\text{Fe}]$ values has been large: For example, Abia & Rebolo (1989) found $[\text{O}/\text{Fe}] = +1.0$ for stars near $[\text{Fe}/\text{H}] = -2.0$, based on the O I triplet at 7774 Å. This result is almost certainly too high, as shown by many investigations (e.g. Barbuy 1988, Bessell et al 1991, Spite & Spite 1991, Kraft et al 1992, Nissen et al 1994). King (1993) suggested that the Abia & Rebolo equivalent widths were too high by approximately 25%, which, when combined with a revision of the temperature scale by 200 K, resolves the differences between the abundance results for O I lines and other oxygen abundance indicators.

The low S/N OH line results of Bessell et al (1991) and Nissen et al (1994) suggest that $[\text{O}/\text{Fe}] = +0.5$ to $+0.6$ dex in the interval $[\text{Fe}/\text{H}] = -1$ to -3.4 . Bessell et al (1991) claimed that the halo $[\text{O}/\text{Fe}]$ ratios continue the slope of the $[\text{O}/\text{Fe}]$ relation with $[\text{Fe}/\text{H}]$ seen in the disk, down to $[\text{Fe}/\text{H}] = -1.7$; below this point the halo $[\text{O}/\text{Fe}]$ ratio is constant.

From high S/N (~ 150) spectra, Barbuy (1988) measured a mean $[\text{O}/\text{Fe}] = +0.35 \pm 0.15$ from the 6300-Å [O I] line in 20 halo giants with metallicities in

the range $-2.5 \leq [\text{Fe}/\text{H}] \leq -0.5$. Kraft et al (1992) and Sneden et al (1991b) measured $[\text{O}/\text{Fe}]$ for many globular cluster giants and 27 field giants from S/N ~ 150 spectra of the $[\text{O I}]$ line. The field giants ranged in $[\text{Fe}/\text{H}]$ from -1.3 to -2.8 with an average $[\text{O}/\text{Fe}] = +0.34$. For oxygen-rich giants in the globular clusters (those without envelope depletion of oxygen) measured by Kraft et al (1992) the mean $[\text{O}/\text{Fe}] = 0.32$.

Balachandran & Carney (1996) measured C and O abundances in a halo dwarf using high S/N spectra of near-infrared OH and CO lines; they also rederived abundances from published O I, $[\text{O I}]$, and C I lines. In particular, the solar and stellar abundances were both computed from the same grid of model atmospheres with the same set of lines. Balachandran & Carney found $[\text{O}/\text{Fe}] = +0.29$ dex for this star and concluded that temperature corrections were not required to resolve differences between forbidden and high excitation O lines, as had been previously suggested by King (1993). The resolution of the high O abundance values of Abia & Rebolo (1989) was due to the use of a self-consistent solar and stellar model atmosphere grid.

The preferred results of Figure 3a indicate a trend of $[\text{O}/\text{Fe}]$ with $[\text{Fe}/\text{H}]$ that is flat between $[\text{Fe}/\text{H}] -1$ to -3 , at $[\text{O}/\text{Fe}] = +0.34$ dex; the dispersion of 0.1 dex about this value is consistent with the measurement uncertainties. Thus, the oxygen abundances in the bulge are consistent with a constant IMF. In Figure 3b I show results from O I triplet lines and low S/N spectra of UV OH lines, which exhibit a large dispersion.

There have been many studies for Mg, Si, Ca, and Ti in halo field stars; some of the more recent examples include those of François (1986), Magain (1987, 1989), Gratton & Sneden (1987, 1988, 1991), Zhao & Magain (1990), Ryan et al (1991), Nissen et al (1994), Fuhrmann et al (1995), McWilliam et al (1995a), and Pilachowski et al (1996). Not surprisingly, the $[\alpha/\text{Fe}]$ ratios from this list encompass a range of values; for calcium, the lowest measured mean ratio for halo stars is $[\text{Ca}/\text{Fe}] = +0.18$ (Gratton & Sneden 1987), and the highest is $[\text{Ca}/\text{Fe}] = +0.47$ (Magain 1989). Much of the scatter in the abundance ratios is probably due to systematic effects in the analysis of different researchers: For example Gratton & Sneden consistently find lower $[\alpha/\text{Fe}]$ ratios than Magain Zhao & Magain; the usual differences are approximately 0.15 dex. Taking straight average abundance ratios for all the above studies gives the following results: $[\text{Mg}/\text{Fe}] = +0.36$, $[\text{Si}/\text{Fe}] = +0.38$, $[\text{Ca}/\text{Fe}] = +0.38$, and $[\text{Ti}/\text{Fe}] = +0.29$, with typical $1\sigma = 0.08$. The average of all four species gives $[\alpha/\text{Fe}] = +0.35$, with $\sigma = 0.05$ dex, which is very close to the adopted value for $[\text{O}/\text{Fe}]$ of $+0.34$ dex. A conservative conclusion is that in the halo, the α elements O, Mg, Si, Ca, and Ti all show an enhancement, relative to Fe, of $+0.35$ dex; alternatively, the full range of measured $[\alpha/\text{Fe}]$ ratios is well represented by $+0.37 \pm 0.08$.

François (1987, 1988) measured sulfur in halo stars from extremely weak, high excitation S I lines near 8694 Å and found $[S/Fe] = +0.6$; given the difficulty associated with abundance measurement of such weak lines, this result is approximately consistent with the general α -element overabundances.

A small slope in the halo relation between $[\alpha/Fe]$ abundance ratios and $[Fe/H]$ may possibly be responsible for part of the dispersion in published abundance results. For example, the McWilliam et al (1995a,b) study has a lower mean metallicity than Gratton & Sneden's (1988, 1991) work, with some overlap; on average McWilliam et al's (1995a,b) $[\alpha/Fe]$ ratios are ~ 0.1 dex higher. However, the six stars common to both studies show a mean difference [McWilliam et al minus Gratton & Sneden] for $[Fe/H]$, $[Mg/Fe]$, $[Si/Fe]$, $[Ca/Fe]$, and $[Ti/Fe]$ of only 0.00, 0.06, -0.08 , -0.03 , and 0.12 dex, respectively. Plots of $[Mg/Fe]$ and $[Ca/Fe]$ by McWilliam et al (1995a,b) showing the comparison with Gratton & Sneden (1988, 1991) could be interpreted as evidence for increases in both ratios with declining $[Fe/H]$.

Gratton (1994) combined the α -abundance results of several studies and found small increases in $[O/Fe]$, $[Ti/Fe]$, and $[Mg/Fe]$ with declining $[Fe/H]$ in the interval $[Fe/H] = -1$ to -3 ; this was claimed to be consistent with an increased production of O, Ti, and Mg at the lowest metallicity by high mass SN. The slopes were also consistent with chemical evolution model predictions of Matteucci & François (1992). Subtle slopes can also be seen in the $[Ca/Mg]$ and $[Ti/Mg]$ results of McWilliam et al (1995a,b), which may indicate a slight decrease in Mg, or an increase in Ca and Ti abundances, at the lowest metallicity. If true, these subtle trends indicate that the halo IMF was not constant with time. However, caution is warranted here because the small gradients could easily be the result of systematic measurement errors. Contrary to the above finding, Nissen et al (1994) concluded from analysis of halo field stars that the halo IMF was constant with time in the interval $-3.5 \leq [Fe/H] \leq -1.8$.

Carney (1996) reviewed α -element abundances in globular clusters and found no evidence for a decline in $[O/Fe]$, $[Si/Fe]$, or $[Ti/Fe]$ from $[Fe/H] = -2.2$ to -0.6 dex. A hint of a decline in $[Ca/Fe]$ with increasing metallicity was found, which might be real but could equally well signal an analysis problem. The conclusion was that there is a uniform enhancement of $[\alpha/Fe] \sim +0.3$ dex in the globular clusters, with no evidence of SN Ia nucleosynthesis products in the younger clusters. The $\sim 3 \times 10^9$ year dispersion in globular cluster ages implies that either the time scale for SN Ia is longer than $\sim 3 \times 10^9$ years or that the "old halo" and "disk" globular clusters do not share a common history; at least one of the classes presumably formed far from the Galaxy and was accreted at a later time. Also, no large changes in IMF occurred during the epoch of globular cluster formation.

In principle, it should be possible to estimate the mean mass of SN that occurred in the halo because SN nucleosynthesis predictions (e.g. Arnett 1991, Woosley & Weaver 1995) indicate that certain ratios (e.g. O/C and O/Mg) are sensitive to progenitor mass. Unfortunately the predictions of the two theoretical papers are not entirely consistent, which makes it difficult to constrain the IMF.

Establishing whether the all α elements exhibit the same level of enhancement in metal-poor stars is important; if so, this would favor a scenario in which the α -element trend is due simply to the addition of iron-peak elements, as suggested by Tinsley (1979). In this regard, McWilliam et al (1995a,b) and Nissen et al (1994) measured [Ti/Fe] values ~ 0.1 dex smaller than enhancements of other α elements (Mg, Si, Ca); McWilliam et al (1995a,b) claimed that this may be evidence that some Ti is produced in SN Ia.

There is increasing evidence for depletion of α elements abundances in some halo stars: Fuhrmann et al (1995) found [Mg/Fe] = -0.28 in BD + 3 740. McWilliam et al (1995a,b) found two stars (CS22968-014 and CS22952-015) near [Fe/H] = -3.4 with [Mg/Fe] < 0.0. These Mg depletions could be primordial, or they could be due to operation of the MgAl cycle in these stars (e.g. Shetrone 1996a,b), although the MgAl cycle would suggest large enhancements of Al, which are not seen in McWilliam et al's (1995a) stars.

Brown et al (1996) found low [α /Fe] ratios in two young globular clusters (Rup 106 and Pal 12), with [Fe/H] of -1.5 and -1.0 , respectively. In Pal 12, [Mg/Fe], [Ca/Fe], and [Ti/Fe] are approximately solar (i.e. below the halo value); in Rup 106, [O/Fe] and [Mg/Fe] are roughly solar, but [Ca/Fe] and [Ti/Fe] ~ -0.2 dex. Recently, Carney (in preparation) found a metal-poor field star with [Fe/H] = -1.9 and subsolar [α /Fe] ratios. The low α -element abundances, compared with the general halo, suggest that these two globular clusters and the field star formed from material with an unusually large fraction of SN Ia ejecta. One explanation is that star formation in the parent clouds proceeded over time scales longer than the time delay for SN Ia. Such an event could occur in low-mass clouds with relatively low star formation rates; because high-mass stars form much less frequently than low-mass stars, a fraction of clouds could be expected to escape SN II for long periods of time and thus permit enrichment by SN Ia. One is reminded of the Taurus molecular cloud, which is currently forming low-mass stars only. Another possibility is that the star and clusters were captured from a companion galaxy, like the LMC, which experienced chemical evolution over an interval of time longer than the characteristic SN Ia time scale.

Bazan et al (1996) found enhanced α -element abundances for a number of "metal-rich" halo stars (compared to the mean halo [Fe/H] value of -1.6 dex); the sample ranges from [Fe/H] ~ -1 to 0.0, with a mean near -0.5 dex. If

confirmed, this shows that the enhanced α -element abundances are a characteristic of the halo as a population, regardless of metallicity. This is supported by the α -element overabundances in Arcturus measured by Balachandran & Carney (1996). This underscores the fact that the knee in the $[\alpha/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ diagram (e.g. Figures 1 and 3) simply represents the intersection of the α -element trends for the halo and disk and does not indicate an evolutionary connection.

Timmes et al (1995) made predictions of Galactic abundance ratios, from H to Zn, based on a Simple chemical evolution model and theoretical nucleosynthesis yields for SN II (from Woosley & Weaver 1995), SN Ia (from Nomoto et al 1984, Thielemann et al 1986), and 1- to 8- $M_{\odot}$ stars (Renzini & Voli 1981). The predicted trends with metallicity for O, Mg, Si, and Ca show reasonable agreement with observations; but the predictions for S lie below the observed $[\text{S}/\text{Fe}]$ ratios and are just barely consistent with the 0.3-dex theoretical uncertainty. The predictions for Ti are by far the worst of all elements; the theoretical $[\text{Ti}/\text{Fe}]$ ratio is almost 0.7 dex below the observed values near $[\text{Fe}/\text{H}] \sim -2$. It is clear that present SN nucleosynthesis calculations completely fail to account for the observed $[\text{Ti}/\text{Fe}]$ ratios in the Galaxy; Ti is significantly enhanced in the bulge and halo, yet nucleosynthesis calculations suggest that it should scale with Fe. Thus, Ti provides an important constraint for SN nucleosynthesis theory.

SOME LIGHT ELEMENTS

Carbon

Carbon is one of those elements that can be greatly affected by late stages of stellar evolution. In the red giant stage, a star will dredge up material processed by the CNO cycle, which results in C depletions, increased ^{13}C , and increased N abundances, and sometimes mild O depletions. In this review, I am mostly concerned with evolution of abundances in the Galaxy as a whole and not with the self-pollution of individual stars, unless this has a significant effect on the Galactic picture. For an excellent discussion of mixing in red giant branch stars, see Kraft (1994), Kraft et al (1997), and Shetrone (1996a,b).

Wheeler et al (1989) reviewed carbon abundances from Peterson & Sneden (1978), Clegg et al (1981), Laird (1985), Tomkin et al (1986), and Carbon et al (1987) and concluded that $[\text{C}/\text{Fe}] \sim 0.0$ independent of $[\text{Fe}/\text{H}]$, but with a possible increase in $[\text{C}/\text{Fe}]$ below $[\text{Fe}/\text{H}] \sim -1.5$.

Recent abundance studies of carbon indicate that $[\text{C}/\text{Fe}]$ is enhanced with declining $[\text{Fe}/\text{H}]$ in the Galactic disk (e.g. Friel & Boesgaard 1992, Andersson & Edvardsson 1994, Tomkin et al 1995), such that at $[\text{Fe}/\text{H}] = -0.8$, $[\text{C}/\text{Fe}] \sim +0.2$. Thus, in the disk $[\text{C}/\text{Fe}]$ and $[\alpha/\text{Fe}]$ show morphologically similar trends with $[\text{Fe}/\text{H}]$.

Tomkin et al (1992) found that $[C/O] \sim -0.6$ for halo dwarfs in the interval $-1 \geq [Fe/H] \geq -2.6$, based on high excitation C I and O I lines. Although the C I and O I results showed evidence of unaccounted non-LTE effects, Tomkin et al suggested that the errors cancel out for the $[C/O]$ ratio. Tomkin et al also measured $[C/Fe]$ from CH lines and found a trend of increasing $[C/Fe]$ with decreasing $[Fe/H]$: Near $[Fe/H] = -1$, $[C/Fe] \sim -0.3$, with the trend suggesting that at $[Fe/H] = -2$, $[C/Fe] \sim 0.0$. Balachandran & Carney (1996) measured C and O from infrared CO and OH lines for one halo dwarf at $[Fe/H] = -1.2$, and they found $[C/Fe] = -0.32$.

Two puzzles arise from the Tomkin et al (1992) halo results: If $[C/O]$ is constant, but $[C/Fe]$ increases with declining $[Fe/H]$, then $[O/Fe]$ must also increase with declining $[Fe/H]$; yet Figure 3a rules out the required 0.3 dex change in $[O/Fe]$ between $[Fe/H] = -1$ and -2 . It is likely that the constant $[C/O]$ ratio implied from the high excitation C I and O I lines may be suspect. The second difficulty, pointed out by Balachandran & Carney (1996), results from the large change in $[C/Fe]$ between the halo and disk at similar metallicity; in the halo $[C/Fe] \sim -0.3$ near $[Fe/H] = -1.2$, while in the disk $[C/Fe] = +0.2$ at $[Fe/H] = -0.8$. According to Balachandran & Carney (1996), this would require a large contribution to Galactic carbon from intermediate-mass stars.

McWilliam et al (1995b) measured $[C/Fe]$ values for 33 halo giants with $-4 \leq [Fe/H] \leq -2$ and combined the results with the sample of Kraft et al (1982); no compelling evidence was found for a deviation of the mean $[C/Fe]$ from the solar ratio. However, when compared with the results of Carbon et al (1987), a slight trend of increasing $[C/Fe]$ could not be ruled out at the level of about 0.07 dex/dex in $[Fe/H]$. In either case, $[C/Fe]$ is roughly constant over a range of 3.5 decades in $[Fe/H]$. McWilliam et al (1995b) found a large scatter in $[C/Fe]$ for their giant sample, with a range of 1.6 dex, which is much larger than the measurement uncertainties. It seems possible that the scatter in $[C/Fe]$ is due to an intrinsic dispersion in composition of the gas that formed the stars. If this is the case, then some of the halo carbon stars may not be the products of nucleosynthesis on the AGB, or mass transfer from an AGB star, but occurred because of stochastic enhancements in the carbon abundance of Galactic gas. This idea was supported by Kipper et al (1996), who claimed to have found at least three objects that formed as intrinsic carbon stars.

Thus, although the disk carbon abundances may resemble the α element pattern, in the halo the abundance trends are quite different and quite uncertain. It is clear that more work is required to properly understand $[C/Fe]$ as a function of $[Fe/H]$; this might best be executed by taking advantage of new infrared spectrometers to measure C and O abundances from lines of CO and OH (as pointed out by Balachandran 1996).

For the bulge, the only carbon abundance measurement is that of A McWilliam, A Tomaney & RM Rich (in progress), who used the published values of the narrowband CO index for several bulge giants to estimate the average bulge $[C/Fe]$ ratio, which was found to be ~ -0.2 dex. This value is consistent with typical $[C/Fe]$ ratios seen in solar neighborhood red giants (Lambert & Ries 1981); the slight deficiency from the solar value is due to the normal red giant dredge-up of material processed though the CN cycle.

Aluminum and Sodium

In the Galactic disk, the $[Al/Fe]$ ratio increases with decreasing $[Fe/H]$, reaching $\sim +0.3$ dex at $[Fe/H] = -1$ (Edvardsson et al 1993, Tomkin et al 1985), but this is only 0.2 dex above the mean $[Al/Fe]$ ratio for solar metallicity stars. In the Edvardsson et al (1993) sample, these stars exhibit a 0.2-dex increase in $[Na/Fe]$ from $[Fe/H] = 0$ to -1 ; however, Tomkin et al (1985) found $[Na/Fe] \sim 0.0$ for their sample. Thus, from a phenomenological point of view, Al and perhaps Na could be classified as mild α elements, even though their nuclei have odd numbers of protons, which is consistent with a significant component of Al and Na synthesis from SN II.

The $[Al/Fe]$ ratio in halo stars spans a range of approximately 2-dex (see Figure 7). The most extensive recent study of Al is that of Shetrone (1996a),

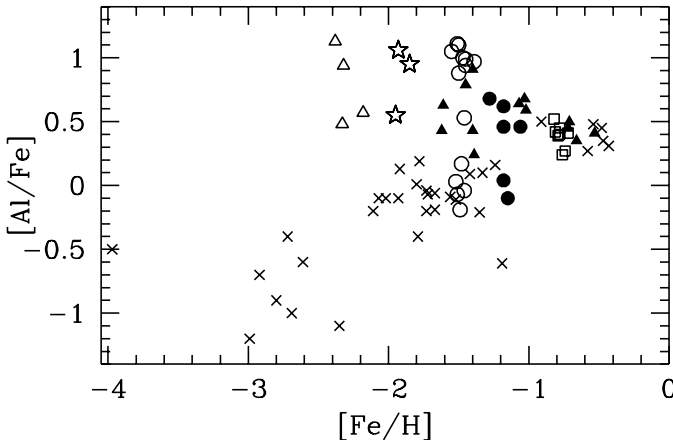


Figure 7 The trend of $[Al/Fe]$ with metallicity for field stars, indicated by crosses (from Shetrone 1996a and Gratton & Sneden 1988), and globular clusters from Shetrone (1996a); open boxes for M71, open circles for M13, filled circles for M5 and open triangles for M92; filled triangles for M22, M4, and 47 Tuc from Brown et al (1992), and open stars for NGC 2298 from McWilliam et al (1992). Note that the lower bound of the globular cluster values is consistent with the field star trend.

who showed that the globular cluster giants and the field halo giants have very different mean $[\text{Al}/\text{Fe}]$ ratios, with little overlap. Shetrone (1996a) showed a plot of $[\text{Al}/\text{Fe}]$ versus spectroscopic luminosity, indicating that the Al difference was not due to luminosity. However, luminosity is difficult to measure for field stars, so a more reliable estimate of the position of a star on the red giant branch for this comparison is the temperature; in this case, there is only a small region of overlap between field and globular cluster stars, near 4300 K. At 4300 K and above, for $[\text{Fe}/\text{H}] \sim -1$, no field giant has $[\text{Al}/\text{Fe}]$ larger than $+0.3$, whereas many globular cluster giants with the same metallicity, luminosity, and temperature have $[\text{Al}/\text{Fe}]$ larger than this value, up to a maximum value near $+1$ dex.

In Figure 7, the lowest $[\text{Al}/\text{Fe}]$ ratios found in globular cluster giants appear similar to the field halo giants. This, at least, is consistent with the idea of self-pollution of Al from proton burning and deep mixing in evolved red giants (e.g. Denisenkov & Denisenkova 1990). In metal-poor stars, the declining $[\text{Al}/\text{Fe}]$ ratio, or $[\text{Al}/\text{Mg}]$, with decreasing metallicity is well known (e.g. Aller & Greenstein 1960, Arpigny & Magain 1980, Spite & Spite 1980) and has long been interpreted as consistent with the metallicity-dependent Al yields from explosive carbon burning, predicted by Arnett (1971). The Arnett predictions indicate that $[\text{Na}/\text{Fe}]$ ratios should also decline with decreasing metallicity, but this is not observed; in fact, $[\text{Na}/\text{Fe}] \sim 0.0$ from $[\text{Fe}/\text{H}] = -1$ to -4 (e.g. McWilliam et al 1995b). Pilachowski et al (1996) analyzed a sample of 60 halo subgiants, giants, and horizontal branch stars in the interval $-3 \leq [\text{Fe}/\text{H}] \leq -1$; they found a small $[\text{Na}/\text{Fe}]$ deficiency of -0.17 dex in the mean and that bright field halo giants do not show the excess of sodium found in their globular cluster counterparts.

Globular cluster giants show large dispersions in Na and Al abundances. The Na and Al abundances are correlated, and they are correlated with N enhancements and O depletions. The abundance patterns have been interpreted either as evidence of internal nucleosynthesis and mixing operating in individual stars or, alternatively, as characteristic of a dispersion in the composition of the material out of which the stars formed (see Kraft 1994 and Shetrone 1996a,b, Kraft et al 1997, and references therein for details). Presently, the source of the Al and Na dispersion remains contested. Thus it is difficult to use Na and Al as probes of Galactic chemical evolution until the effects of individual stars can be quantified.

Studies of globular cluster main-sequence stars suggest that there may be a problem with the notion that globular clusters formed from chemically homogeneous material. Briley et al (1991) observed 10 main-sequence stars in 47 Tuc and found the same frequency of CN bimodality as present in the more evolved giant sequences; later, Briley et al (1996) found correlated CN and Na enhancements in main-sequence stars of the globular cluster 47 Tuc. These abundances,

if found in giant branch stars, would have been attributed to dredge-up of internal nucleosynthesis products, i.e. self-pollution; however, this is not possible for main-sequence stars. Therefore, it is most likely that either Briley's CN and Na results are due to mass transfer from evolved companions, or the stars in 47 Tuc were formed from gas that was inhomogeneous in C, N, and Na. In this regard, it is interesting that the high frequency of CN-strong stars (near 50%) far exceeds the frequency in the field (at 5%). Spiesman (1992) found a nitrogen-rich metal-poor dwarf with Na and Al enhanced by +0.5 dex; citing the difficulty in producing Na and Al enhancements in main-sequence stars, Spiesman concluded that in this star the N, Na, and Al abundance anomalies are primordial. Suntzeff (1989) found an anticorrelation between CN and CH for main-sequence stars in NGC 6752. Pilachowski & Armandroff (1996) used a fiber spectrograph to acquire spectra of the [O I] region, at 6300 Å, for 40 stars at the base of the giant branch in M13. These stars are not expected to show oxygen depletions in the standard theory (e.g. Kraft 1994). The combined spectrum was of high S/N (~ 300), yet the undetected [O I] line indicated a limiting oxygen abundance below the solar [O/Fe] ratio; such deficiencies have been interpreted in the past as due to red giant evolution.

Comprehending Al in globular cluster giants will have to await careful abundance analysis of larger samples of globular cluster main-sequence and red giant branch stars; only then will it be possible to know the scale of the Al production on the giant branch. This is an area in which the new large telescopes can make a significant impact. If the Al and Na abundance anomalies are due to primordial inhomogeneities in the cluster composition, there would be significant implications for ideas of globular cluster formation.

The sample of Galactic bulge giants studied by McWilliam & Rich (1994) also show marked Al enhancements, at approximately +0.7 dex, even at solar metallicity. This observation is consistent with self-pollution by evolved giants because the bulge stars observed were fairly luminous; however, this does not constitute proof of the self-pollution picture.

HEAVY ELEMENTS

In this review I refer to heavy elements as those elements beyond the iron peak, with nuclear charge $Z \geq 31$. The reader is directed to Meyer (1994), Busso et al (1995), Lambert et al (1995b), and Käppeler et al (1989) for more detailed discussions of heavy element synthesis. Elements beyond the iron peak cannot be efficiently produced by charged-particle interactions owing to the large Coulomb repulsion between nuclei; temperatures high enough to overcome the Coulomb barrier tend to photodisintegrate even the iron-peak nuclei (e.g. Woosley & Weaver 1995). Burbidge et al (1957) showed that heavy

elements can be synthesized by successive neutron captures onto iron-peak nuclei, followed by β decays.

The neutron captures can occur on a time scale long enough for all β decays to occur, which is called the s-process (for slow neutron capture), or on a time scale that is short compared to β decay, called the r-process (for rapid neutron capture); these two processes lead to two characteristic abundance patterns.

In a steady flow of neutrons the abundance of each isotope is inversely proportional to its neutron capture cross section. The closed neutron shells with 50, 82, and 126 neutrons have small neutron capture cross sections, leading to abundance peaks for these nuclei. Similarly, even-numbered nuclei have smaller neutron capture cross sections than odd-numbered nuclei, resulting in higher abundances for the even nuclei; this is called the odd-even effect. The s-process abundance pattern is characterized by abundance peaks near mass numbers 87, 138, and 208 neutrons and a strong odd-even effect. The r-process abundance pattern is characterized by the abundance peaks shifted to mass numbers near 80, 130, and 195 with no odd-even effect.

Seeger et al (1965) showed that observed abundances of s-process-only isotopes can be represented by an exponential distribution of neutron exposures. For the Solar System material, the heavy element abundance pattern is best fit by a combination of two s-process exponentials (e.g. see Käppeler et al 1989): (a) the weak component, which corresponds to the light elements $A \leq 85$ (thought to occur in the cores of massive stars, $M \geq 10 M_{\odot}$; see Raiteri et al 1991–1993), and (b) the main component, which fits the region approximately between Rb and Pb.

The s-process main component is thought to occur during the thermal pulse stage of low-mass ($1\text{--}3 M_{\odot}$) AGB stars at neutron densities of $10^7\text{--}10^9 \text{ cm}^{-3}$. Quantitative calculations of AGB (asymptotic giant branch) nucleosynthesis were first performed by Iben (1975) and Truran & Iben (1977). Iben & Truran (1978) estimated that AGB nucleosynthesis in intermediate mass AGB stars could account for a significant fraction of the Galactic abundances of carbon and s-process elements. Since that time, much observational and theoretical work has converged on the idea that the s-process occurs during the AGB phase of low-mass stars (e.g. see Busso et al 1995, Lambert et al 1995b), between the H and He burning shells with neutrons liberated by the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction.

Smith & Lambert (1990) showed that the observed s-process abundances in M, MS, and S stars indicate a mean neutron exposure of $\tau_0 \sim 0.3$ at 30 keV. Because this is equal to the Solar System neutron exposure, it is consistent with AGB s-process nucleosynthesis as a major supply of the main component of the Solar System s-process elements. Recent observational information on the conditions of AGB s-process nucleosynthesis has come from neutron densities inferred from measurements of Rb and Zr isotopic abundances (Lambert et al 1995b).

Another exciting area of AGB nucleosynthesis research involves the study of presolar grains, embedded in meteorites (see Zinner 1996). Anomalous isotopic abundances of carbon and s-process elements in SiC grains indicate a carbon star origin (e.g. Anders & Zinner 1993). Boothroyd et al (1994) and Wasserberg et al (1995) infer the presence of deep circulation currents in AGB stars from the $^{12}\text{C}/^{13}\text{C}$ and $^{18}\text{O}/^{16}\text{O}$ ratios in these grains.

The site of the r-process is still in debate, although SN have been suspected from the beginning (Burbidge et al 1957). The most popular model is due to Meyer et al (1992), who suggested that the r-process occurs in the hot high-entropy bubble surrounding the nascent neutron star during the SN explosion. In this region, the high photon-to-baryon ratio favors photodissociation, thus keeping the number of free neutrons high and the number of nuclei low. Once the material cools, the nuclei are exposed to a sea of neutrons, at neutron densities of $\sim 10^{20} \text{ cm}^{-3}$, which drives the r-process.

Disk and Bulge Heavy Elements

The notion that most heavy elements scale with $[\text{Fe}/\text{H}]$ in the disk has been known for some time (e.g. Wallerstein 1962, Helfer & Wallerstein 1968, Pagel 1968, Huggins & Williams 1974, Butcher 1975). The most accurate and largest samples of disk dwarf abundances are the studies of Edvardsson et al (1993) and Woolf et al (1995); also McWilliam (1990) presented abundance results for a large number of disk giants.

The Edvardsson et al results demonstrate that the abundance of Y in the first s-process peak, and Ba and Nd in the second s-process peak, scale with metallicity down to $[\text{Fe}/\text{H}] = -1$. This observation is apparently at odds with the picture of primary and secondary elements: The s-process elements are made by the addition of neutrons to preexisting iron seed nuclei. Thus, the [s-process/Fe] abundance ratios are expected to behave like secondary elements, proportional to $[\text{Fe}/\text{H}]$, rather than independent of the metallicity, as is observed. Clayton (1988) proposed that s-process abundances scale with metallicity if they were produced by the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ neutron source in AGB stars; also, the increased neutron fluence in the model led to the prediction of increased $[\text{Ba}/\text{Y}]$ ratios at low metallicity. This prediction was supported by the observed high $[\text{Ba}/\text{Y}]$ abundance ratios found for CH stars (Vanture 1992, 1993) and ω Cen giants (e.g. Vanture et al 1994) and the abundance ratios in S and MS stars (see Busso et al 1995).

The metallicity dependence of the $[\text{Ba}/\text{Y}]$ ratio produced in the s-process leads to a puzzle: If AGB stars are the source of the s-process elements in the disk, then why is the observed $[\text{Ba}/\text{Y}]$ ratio approximately ~ 0.0 dex over the full metallicity range of disk stars?

Part of the answer must be due to the transition from halo-like composition ($[\text{Ba}/\text{Y}] = +0.06$) gas near $[\text{Fe}/\text{H}] = -1$ to solar composition at $[\text{Fe}/\text{H}] = 0.0$;

both have similar $[\text{Ba}/\text{Y}]$ values. Perhaps a more important factor is the presence of a large metallicity dispersion in the disk over most of Galactic history. In particular, the inhomogeneous chemical evolution models of White & Audouze (1983) showed that when there is a large dispersion in metallicity, the slopes for secondary elements can be erased; this is because at any given time the secondary elements were produced in sources with a large range of metallicity. Thus, the metallicity dispersion ensured that the $[\text{Ba}/\text{Y}]$ ratio in the disk was always close to the average value.

Woolf et al (1995) measured $[\text{Eu}/\text{Fe}]$ ratios in solar neighborhood F and G stars with $-0.9 \leq [\text{Fe}/\text{H}] \leq +0.3$. Their results showed increasing $[\text{Eu}/\text{Fe}]$ ratios with decreasing $[\text{Fe}/\text{H}]$; this trend was also reported by McWilliam & Rich (1994), although there was some considerable scatter about the mean relation. The $[\text{Eu}/\text{Fe}]$ ratios match the trend of increasing α -element abundances with $[\text{Fe}/\text{H}]$; from the $[\text{Eu}/\text{Fe}]$ trends in the disk and the halo, one would classify Eu as an α element. Because Eu is a nearly pure r-process element, the observed trend with metallicity is consistent with the notion that the r-process and α elements are made in SN II (see Figure 8). For stars more metal-rich than the Sun, Woolf et al (1995) found subsolar $[\text{Eu}/\text{Fe}]$ ratios, unlike the $[\alpha/\text{Fe}]$ ratios that remain at the solar value above solar metallicity. The idea proposed by Maeder (1991) to explain the trend of $[\text{O}/\text{Fe}]$ with $[\text{Fe}/\text{H}]$ as due to the onset of Wolf-Rayet stars would have to affect the $[\text{Eu}/\text{Fe}]$ ratio in the same way as

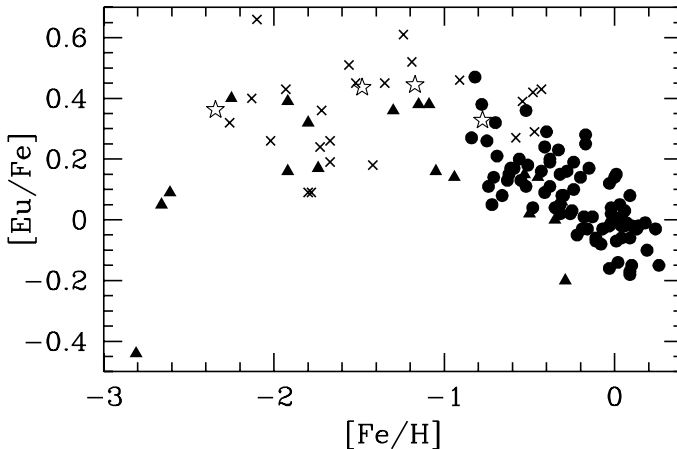


Figure 8 The run of the (almost) pure r-process element europium with metallicity for field stars; indicated by *filled circles* for the disk (Woolf et al 1995) and in the halo by *crosses* (Shetrone 1996a) and *filled triangles* (Gratton & Sneden 1994). The *open stars* indicate mean values for the globular clusters M71, M13, M5, and M92 from Shetrone (1996a).

the [O/Fe] ratios. It is difficult to imagine how such a process might occur in current models of SN II, which holds that Eu is formed during the SN II event, deep inside the exploding star, whereas the ejected O is produced in higher regions of the star during the hydrostatic burning phase.

The Zr results from Edvardsson et al (1993) show a trend towards enhanced [Zr/Fe], reaching +0.2 dex in the lower metallicity disk stars; given the enhanced [Zr/Fe] ratios in the halo stars (Magain 1989, Gratton & Sneden 1994), this may suggest that SN II produce significant amounts of Zr.

Edvardsson et al (1993) showed that in the disk, [Ba/Fe] ratios increased with time and were very roughly independent of metallicity; from log age ≥ 0.9 to < 0.6 Gyr, the mean [Ba/Fe] ratio increased from -0.1 to $+0.1$ dex. The halo fits into this picture, with a mean [Ba/Fe] ratio of ~ -0.1 dex (Gratton & Sneden 1994). This trend in [Ba/Fe] suggests that there is a source that produced Ba on a time scale longer than the time scale for Fe production. This conclusion is consistent with the idea that s-process nucleosynthesis is dominated by AGB stars over the mass range $1-3 M_{\odot}$ (Meyer 1994) or $1-4 M_{\odot}$ (Busso et al 1995). The steady increase in the disk [Ba/Fe] ratio with Galactic time is probably due to the delay in Ba production from the lower mass stars in this range, say $1-2 M_{\odot}$, with main-sequence lifetimes of several billion years.

The results of Edvardsson et al (1993) show a steeper slope for [Ba/H] with age than [Fe/H] with age; also, despite the larger measurement uncertainties for Ba, the age-[Ba/H] relation shows less dispersion than the age-[Fe/H] relation. The steep slope of [Ba/H] with age must be due in part to the gradual increase in [Ba/Fe] with time due to the long-lived sources. If the intrinsic dispersion in the age-[Ba/H] relation is actually significantly smaller than for the age-[Fe/H] relation, then this must be understood in the context of disk chemical evolution models that describe the dispersion in the age-metallicity relation (e.g. Pilyugin & Edmunds 1996b). A characteristic of the Pilyugin & Edmunds (1996b) model is that it predicts roughly equal dispersion for *all* elements.

The fact that the [Ba/Fe] ratio is sensitive to age might have applications for other locations, such as the Galactic bulge. For the bulge, McWilliam & Rich (1994) found the mean [s-process/iron] ratio of ~ 0.0 dex, from lines of Y, La, and Ba. In particular, a subsolar value of [s-process/Fe] near -0.1 dex, expected if the bulge formation time scale was rapid, is inconsistent with the data. Certainly more accurate and extensive measurements of s-process elements in the bulge are necessary to verify this point.

Halo Heavy Elements

To summarize the principle result of this section: Heavy element abundances in the halo are characterized by a significant r-process component and a 300-fold dispersion in [heavy element/Fe] ratios below [Fe/H] = -2.5 at about a

constant average value. The pattern of r-process nucleosynthesis in the halo heavy element abundances provides evidence that this dispersion reflects an inhomogeneous composition of the material from which the stars formed, and the observed [heavy element/Fe] values set the minimum [heavy element/Fe] range from SN II events. The decreasing dispersion with increasing metallicity is consistent with a gradual homogenization of low metallicity gas by the process of averaging yields from individual SN events.

Although present in the abundance results of Wallerstein et al (1963) Pagel (1968) was the first to recognize that very metal-poor halo stars show heavy element deficiencies. Evidence for a plateau with [heavy element/Fe] ~ 0.0 , followed by a systematic trend of decreasing [heavy element/Fe] below [Fe/H] ~ -2.5 , was presented by Spite & Spite (1978, 1979), Luck & Bond (1981, 1985), Barbuy et al (1985), Gratton & Sneden (1988), Magain (1989), and Zhao & Magain (1990, 1991). In particular, the results of Gilroy et al (1988) and Magain (1989) showed that [Eu/Fe] and [Zr/Fe] are enhanced in the interval [Fe/H] = -1.5 to -2.5 .

Perhaps the most accurate abundance results for the largest sample of heavy elements come from Gratton & Sneden (1994), with stars in the interval $-3 \leq [\text{Fe}/\text{H}] \leq -0.5$. The abundance ratios [M/Fe] for Sr, Y, Ba, La, Ce, and Nd lie approximately between [M/Fe] ~ 0.00 to ~ -0.1 dex, and Zr, Sm, Pr, Dy, and Eu are enhanced relative to the solar composition. The ~ 0.3 -dex enhancement in [Eu/Fe] is notable because Eu is an almost pure r-process element, thought to be produced only in SN II; its enhancement resembles the ~ 0.3 -dex enhancement observed for the α elements in the halo, which are also thought to be produced only in SN II.

The first evidence for a heavy element abundance dispersion in halo stars was due to Griffin et al (1982), who found heavy element enhancements in HD 115444. Luck & Bond (1985) found several halo stars with Ba and Sr enhancements. Both studies suggested that stars with heavy element enhancements were population II barium stars.² Gilroy et al (1988) claimed an r-process pattern and a large abundance dispersion for the halo heavy elements, which was consistent with heavy element abundance scatter in the material from which the stars formed. Ryan et al (1991) also claimed a dispersion in heavy element abundances larger than the measurement errors.

However, Baraffe & Takahashi (1993) suggested that the scatter was due entirely to measurement errors, based on the large scatter in published heavy element abundances for individual stars. The accurate abundance measurements of Gratton & Sneden (1994) indicated a heavy element dispersion of less than 0.1 dex for their sample, consistent with their measurement uncertainties.

²Barium stars are thought to arise from mass transfer from an AGB star that has polluted its envelope with s-process elements (e.g. McClure 1984).

McWilliam et al (1995a,b) analyzed a large sample of extremely metal-poor halo stars from the survey of Beers et al (1992), in the metallicity range $-4 \leq [\text{Fe}/\text{H}] \leq -2$, and made reliable estimates of the measurement uncertainties. They found a decline in [heavy element/Fe] below $[\text{Fe}/\text{H}] = -2.5$, accompanied by a considerable scatter in [Sr/Fe] and [Ba/Fe] abundance ratios, with a range of 2.5 dex (see Figure 9); typical measurement uncertainties were ± 0.2 dex. This scatter does not conflict with the small dispersion found by Gratton & Sneden (1994) because the Gratton & Sneden sample included only two stars below $[\text{Fe}/\text{H}] = -2.5$.

Ryan et al (1996) analyzed additional extremely metal-poor stars and found a large scatter in heavy element abundances for metal-poor halo dwarfs and giants, consistent with a primordial abundance scatter.

The McWilliam et al results show that for both [Sr/Fe] and [Ba/Fe] the mean ratios are the same above and below $[\text{Fe}/\text{H}] = -2.5$. Although there are many more stars deficient in heavy elements than with overabundances, the few heavy element-rich stars cause the average [Sr/Fe] and [Ba/Fe] ratios to be near the solar value. This explains why early studies found a trend of declining heavy element/Fe ratios as $[\text{Fe}/\text{H}]$ declined; there is no trend, only a lower envelope of the dispersion that is skewed to low [Sr/Fe] and [Ba/Fe] ratios. Small samples preferentially picked the low [M/Fe] ratio stars because they are more frequent than the stars with heavy element enhancements.

Pagel (1968) and Truran (1981) noted that the near-solar value of the [heavy element/Fe] ratio in the halo implies that the formation time for these elements must be shorter than the lifetimes of stars that produce s-process elements. Truran concluded that the heavy elements in the halo were made in massive stars by the r-process.

Abundance studies of halo stars by Sneden & Parthasarathy (1983), Sneden & Pilachowski (1985), and Gilroy et al (1988) indicated heavy element abundance patterns consistent with nucleosynthesis dominated by the r-process.

The [Ba/Eu] ratio is particularly sensitive to whether nucleosynthesis of the heavy elements occurred by the s-process or r-process. The ubiquitous subsolar [Ba/Eu] ratios in halo stars (e.g. Magain 1989, François 1991, Gratton & Sneden 1994, McWilliam et al 1995b) show that the halo must contain a larger fraction of r-process material than the solar composition (e.g. Spite 1992). Figure 10 shows a compilation of [Ba/Eu] and [La/Eu] ratios for field halo stars, with pure r-process and s-process values indicated. The subsolar ratios indicate a larger fraction of r-process material than in the Solar System material; however, some s-process contribution may be required.

Cowan et al (1996) measured abundances of the r-process peak elements Os and Pt from UV lines in the metal-poor halo giant HD126238 ($[\text{Fe}/\text{H}] = -1.7$). When combined with abundances based on optical spectra, the best-fit heavy element pattern contains 80% r-process and 20% Solar System mixture. This

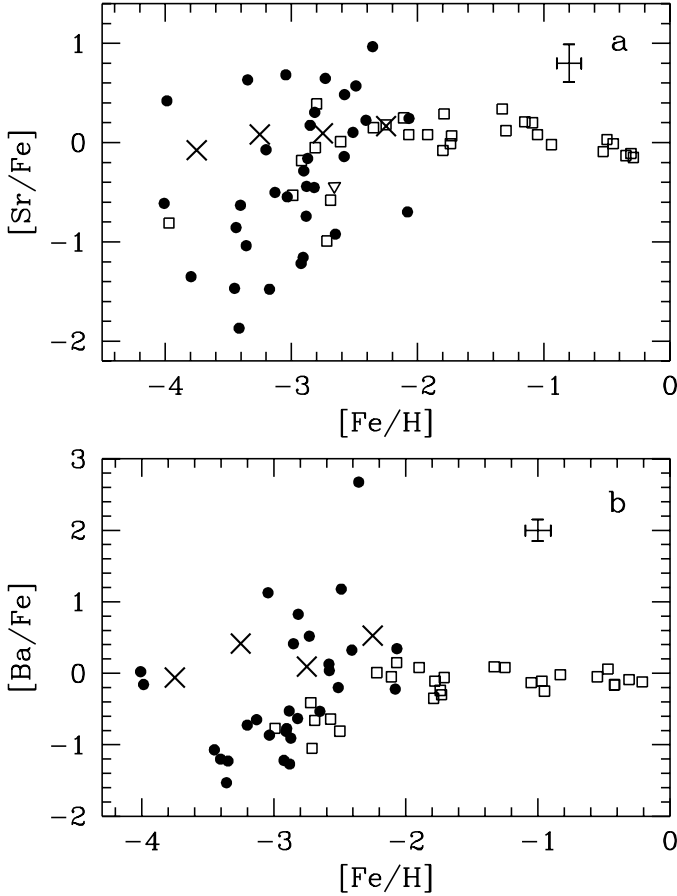


Figure 9 Plots of $[Sr/Fe]$ and $[Ba/Fe]$ from McWilliam et al (1995; *filled circles*) and Gratton & Sneden (1994, 1988; *open squares*). The error bars indicate 1σ uncertainties on the McWilliam et al results. The general run of the $[Sr/Fe]$ data indicates a downward trend below $[Fe/H] = -2.5$ with a dispersion of ~ 300 -fold. The *large crosses* represent the average $[Sr/Fe]$ and $[Ba/Fe]$ ratios for the McWilliam et al sample taken for 0.5-dex bins. The $[Ba/Fe]$ data are similar to the $[Sr/Fe]$ trend, but there is a hint of a bifurcation. Note that the star at $[Fe/H] = -2.36$ and $[Ba/Fe] = +2.67$ represents CS 22898-027, a CH subgiant, which is contaminated by s-process material accreted from an evolved companion, and so was not included in the average.

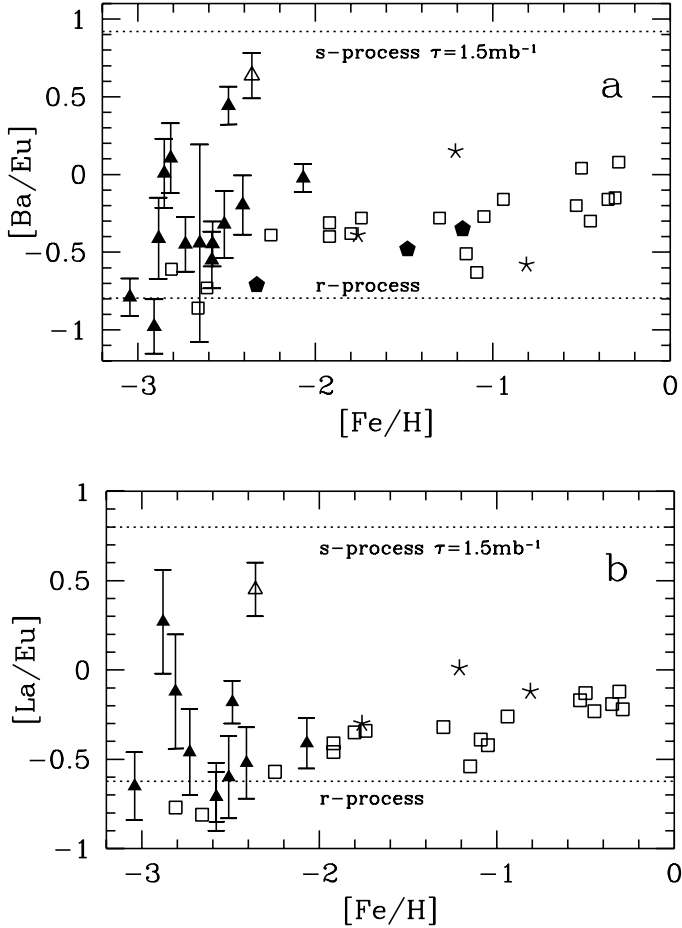


Figure 10 (a) The trend of $[Ba/Eu]$ versus $[Fe/H]$ and (b) $[La/Eu]$ versus $[Fe/H]$; field stars represented by open boxes (Gratton & Sneden 1994) and triangles (McWilliam et al 1995). Star symbols represent mean globular cluster values from Brown et al (1992), and filled pentagons indicate globular clusters from the data of Shetrone (1996a) and Armosky et al (1994). The open triangle indicates the CH subgiant, CS 22898-027, which is contaminated by s-process material. Dashed lines indicate the observed solar system r-process ratio (Käppeler et al 1989) and an extreme s-process value from Malaney (1987).

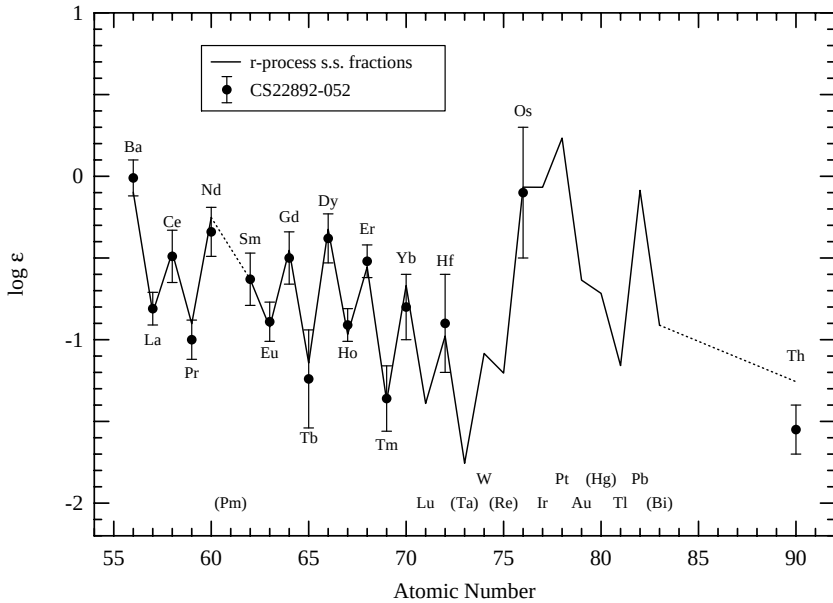


Figure 11 The heavy element abundance pattern in star CS 22892-052, from Sneden et al (1996), scaled to the barium abundance. The line represents the observed Solar System r-process abundance pattern from Käppeler (1989). The excellent agreement suggests that nucleosynthesis was dominated by the r-process; the small scatter about the r-process line indicates that the error bars were overestimated.

is consistent with the value of $[La/Eu] = \sim -0.4$ for halo stars in the range $-2 \leq [Fe/H] \leq -1$ seen in Figure 10.

Element abundances for the most heavy element rich star known, CS 22892-052, were measured by Sneden et al (1994), Cowan et al (1995), McWilliam et al (1995b), and Sneden et al (1996). Figure 11 shows the heavy element abundance pattern in this star, for elements heavier than Ba, which is identical to the Solar System r-process pattern (Käppeler et al 1989). Based on the large r-process overabundance and low $[Fe/H]$, these authors concluded that the heavy elements in CS 22892-052 are dominated by the nucleosynthesis products of a single SN event. This does not mean that all the elements in this star are dominated by SN nucleosynthesis from a single event, only the heavy elements.

Cowan et al (1995) showed that some s-process contribution would help the fit to the observed Sr and Y abundances in CS 22892-052, but the Zr abundances cannot be explained by the s-process; thus the r-process probably at least contributes to the Zr abundance in the Sr-Y-Zr peak. McWilliam et al (1995b)

showed that the $[\text{Sr}/\text{Ba}]$ ratio is approximately constant in halo stars, despite the factor of 300 range of barium abundance due to the r-process. Therefore, if Sr has a significant contribution from the s-process, then the s-process to r-process ratio must be roughly constant in the halo; an alternative is that the r-process is a dominant source of Sr in the halo.

Magain (1995) measured the abundances of barium isotopes in one halo star in order to find the relative contribution of r- and s-process nucleosynthesis, from a profile fit to the Ba II line at 4554 Å. The best-fit profile indicated a Solar System mixture of barium isotopes, contrary to that expected from r-process nucleosynthesis. To resolve the discrepancy with element abundance ratios it would be very useful to have Ba isotopic compositions for a larger sample, especially for stars with both strong and weak Ba II lines.

François (1996) also disputed the claimed r-process source of halo heavy elements, based on a plot of $[\text{Eu}/\text{H}]$ versus $[\text{Ba}/\text{H}]$, arguing against the break in slope of the $\epsilon(\text{Ba})$ versus $\epsilon(\text{Eu})$ seen by Gilroy et al (1988). However, it is better to rely on diagnostic abundance ratios (like $[\text{Ba}/\text{Eu}]$ and $[\text{La}/\text{Eu}]$) as a discriminant of the nuclear reactions involved, rather than on the presence or absence of a break in slope.

Snedden et al (1996) noted that total Ba abundances measured from strong Ba lines in halo stars depend upon the assumed r- and s-process fractions. This effect may result in a downward revision of many previously reported Ba abundances by ~ 0.1 to 0.2 dex and bring earlier measurements of the $[\text{Ba}/\text{Eu}]$ ratio closer to the pure r-process value. Therefore, when considering published abundances, it is best to use Ba abundances based on weak lines or to substitute the abundance of the s-process element La in place of Ba, because lanthanum is dominated by a single isotope (99.9% ^{139}La) with relatively weak lines.

Many astrophysical environments have been proposed as the main source of the r-process. Mathews & Cowan (1990) and Mathews et al (1992) list many of these and attempted to test the possibilities by comparing predicted abundances from a Simple model of Galactic chemical evolution to observed heavy element abundances. They claimed that low-mass SN II ($7\text{--}8 M_{\odot}$) were the most likely candidates. In their model the trend of increasing [heavy element/Fe] ratios with $[\text{Fe}/\text{H}]$ was due to a time delay arising from the longer main-sequence lifetime of low-mass SN II progenitors relative to high-mass SN II progenitors. Thus at early times, when the lowest metallicity prevailed, only high mass SN II occurred with low [heavy element/Fe] yield ratios; at later times, and higher metallicity, the low mass SN II enriched the Galactic gas with high [heavy element/Fe] material. This model requires that in all situations the first low-mass SN II events were preceded by high-mass SN II events, which probably would not occur in the case of chemical evolution in molecular cloud size masses or Searle-Zinn fragments (Searle & Zinn 1978). The model also requires that the

mean $[\text{Sr}/\text{Fe}]$ ratio increases with increasing $[\text{Fe}/\text{H}]$ at low metallicity; however, the results of McWilliam et al (1995b) indicate a constant average $[\text{Sr}/\text{Fe}]$ value. Thus, the time-delay mechanism cannot be used to explain the observed heavy element abundances in the halo, and no constraint can be placed on the mass of the SN chiefly responsible for heavy element synthesis.

McWilliam et al (1995a,b, 1996) and Sneden et al (1994) argued that the observed dispersion in heavy element abundances must reflect an intrinsic dispersion in the $[\text{heavy element}/\text{Fe}]$ ratio of the gas from which the extremely metal-poor halo stars formed. In particular, the r-process abundance pattern and the high frequency of stars with heavy element enhancements rules out the possibility that these stars are population II barium stars.

The heavy element dispersions found by McWilliam et al (1995a,b) showed that the range in SN heavy element yields is at least a factor of 300. McWilliam et al (1996) argued that because the heavy element/Fe ratio for CS 22892-052 is ~ 15 times the asymptotic value, the progenitor SN must represent no more than $1/15$ of all SN II. Because homogenization of the halo gas could only have occurred once the full range of SN yields was sampled, the metallicity of the homogenization point (at $[\text{Fe}/\text{H}] = -2.5$) corresponds to approximately 15 SN events. If $0.1 M_{\odot}$ of iron is ejected per SN II event, then this metallicity requires mixing of the ejecta with $\sim 10^5$ to $10^6 M_{\odot}$ of hydrogen.

Searle & McWilliam (1997 in progress) have studied models of chemical enrichment by small numbers of SN II events, with $[\text{Sr}/\text{Fe}]$ yields selected at random from the observed range in $[\text{Sr}/\text{Fe}]$. This stochastic model can reproduce the average, the dispersion, and the envelope of $[\text{Sr}/\text{Fe}]$ values seen in metal-poor halo stars, with $[\text{Fe}/\text{H}] \leq -2.5$. The model is consistent with enrichment by single SN II events below $[\text{Fe}/\text{H}] \sim -3.3$, in regions of mass $\sim 10^6 M_{\odot}$, which is characteristic of present-day molecular clouds.

The large r-process enhancements in CS 22892-052 allowed Sneden et al (1996) to measure the abundance of thorium (Th, a pure r-process element) in this star. Owing to its 14×10^9 year half life, Th is potentially a useful Galactic chronometer (e.g. Butcher 1987). Based on the solar $[\text{Th}/\text{Eu}]$ ratio, Sneden et al (1996) deduced a minimum age for CS 22892-052 of $15 \pm 4 \times 10^9$ years. Cowan et al (1997) employed r-process nucleosynthesis calculations and various Galactic chemical evolution models to predict the initial r-process $[\text{Th}/\text{Eu}]$ ratio, which led to a minimum age of $15 \pm 4 \times 10^9$ years and a most likely age of $17 \pm 4 \times 10^9$ years.

The early work of Pilachowski et al (1983) indicated low, and even subsolar, $[\text{Eu}/\text{Fe}]$ ratios for globular cluster stars; taken at face value these results suggest a difference between the composition of halo field stars and globular cluster stars. However, the more recent of François (1991), Brown & Wallerstein (1992), Shetrone (1996a), and McWilliam et al (1992) all indicate globular cluster

[Eu/Fe] ratios near +0.4 dex, which is similar to the results for halo field stars (e.g. Gratton & Sneden 1994, Shetrone 1996a, McWilliam et al 1995a,b, Magain 1989, recomputed here); the mean halo [Eu/Fe] value is +0.33 dex, which is the same enhancement as seen in the most metal-poor disk stars (Woolf et al 1995).

The chemical composition of the unusual globular cluster ω Cen differs from other globular clusters and field halo stars. Several recent abundance studies of ω Cen giants have been published: Vanture et al (1994), Norris & Da Costa (1995), Smith et al (1995), and Norris et al (1996). The cluster shows a metallicity spread from $[\text{Fe}/\text{H}] = -1.9$ to -0.6 , with evidence for two star formation epochs. The $[\alpha/\text{Fe}]$ ratios show the normal factor of 2 enhancement seen in halo stars, which implicates nucleosynthesis by SN II only. However, the heavy elements are enhanced well above the solar value and are consistent with significant contamination by s-process nucleosynthesis from AGB stars. This is evidence that the s-process occurs more rapidly than the time scale for enrichment by SN Ia. A puzzle noted by Smith et al (1995) is the subsolar [Eu/Fe] ratio, near -0.4 dex; if AGB stars produced s-process material, then SN II should have produced larger [Eu/Fe] ratios. It is as if the r-process SN II never occurred in ω Cen; perhaps this is an indication of a unique IMF that excluded r-process SN II events.

IRON-PEAK ELEMENTS

The iron-peak elemental abundances showing conclusive evidence for deviations from the solar ratios are summarized in Figure 12. Wallerstein (1962) and Wallerstein et al (1963) were the first to find evidence of a nonsolar mixture of iron-peak elements: Deficiencies of Mn found by Wallerstein were confirmed by later studies (e.g. Gratton 1989). From $[\text{Fe}/\text{H}] = 0.0$ to -1.0 , the $[\text{Mn}/\text{Fe}]$ ratios are deficient in a manner that mirrors the α -element overabundances, and in the interval $[\text{Fe}/\text{H}] = -1.0$ to -2.5 dex, $[\text{Mn}/\text{Fe}]$ is constant at ~ -0.35 dex. Thus the $[\text{Mn}/\text{Fe}]$ trend is similar, but in an opposite sense to the $[\alpha/\text{Fe}]$ trend with $[\text{Fe}/\text{H}]$. A simple conclusion is that a significant source of Mn comes from SN Ia. McWilliam et al (1995a) discovered that below $[\text{Fe}/\text{H}] \sim -2.5$, the $[\text{Mn}/\text{Fe}]$ ratio decreases steadily with decreasing $[\text{Fe}/\text{H}]$, like the trends exhibited by the heavy elements.

Wallerstein's (1962, 1963) observation of Mn deficiencies at low metallicity was claimed to be part of the neutron-excess-dependent yields of Arnett (1971). Even the recent Galactic nucleosynthesis predictions of Timmes et al (1995), based on the Woosley & Weaver (1995) calculations for SN II, predict deficiencies of Sc, V, Mn, and Co of ~ -0.5 dex relative to Fe for metal-poor stars. Wallerstein claimed that V is also deficient in metal-poor stars, but this finding was not confirmed by subsequent analyses (e.g. Pagel 1968). The abundance

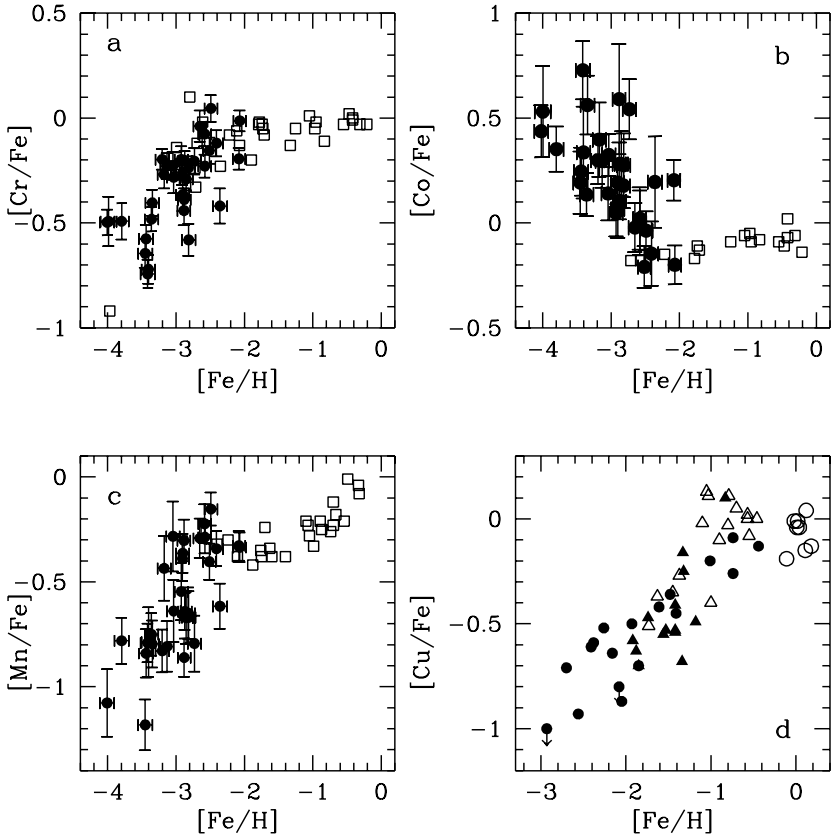


Figure 12 Iron-peak abundance trends for elements that deviate from the solar $[M/Fe]$ ratios. (a–c) Halo field stars: filled circles (McWilliam et al 1995), open squares (Gratton & Sneden 1988, 1991, Gratton 1988). Note that Cr, Co, and Mn each show a decline relative to Fe below $[Fe/H] = -2.5$; $[Mn/Fe]$ also declines between $[Fe/H] = 0.0$ to -1 . (d) $[Cu/Fe]$ versus $[Fe/H]$ from Sneden et al (1991): filled circles (field stars), filled triangles (globular clusters), open triangles (reanalyzed field star data), open circles (literature values for population I field stars).

of V has not been well studied. The most comprehensive analysis was done by Gratton & Sneden (1991), who found $[V/Fe] \sim 0.0$ at all metallicities, which confirmed Pagel's conclusion. If the Mn deficiencies are due to a neutron-excess dependence, then V and Sc are also expected to follow the same trend, which is not observed.

Sneden & Crocker (1988) and Sneden et al (1991a) studied the abundances of Cu and Zn as a function of metallicity and discovered that $[Cu/Fe]$ decreases

linearly with declining metallicity, $[\text{Cu}/\text{Fe}] = 0.38[\text{Fe}/\text{H}] + 0.15$ (curiously the trend resembles that of $[\text{Al}/\text{Fe}]$ with $[\text{Fe}/\text{H}]$), while Zn is constant, at $[\text{Zn}/\text{Fe}] = 0.0$, for all metallicities. Sneden et al suggested that nucleosynthesis of Cu may occur mainly by the weak s-process in the cores of massive stars, with a small contribution from explosive burning in SN II. However, Matteucci et al (1993) suggested that the greatest production of Cu and Zn occurs in SN Ia. If this is true, then some SN Ia occurred for $[\text{Fe}/\text{H}] < -1$, which will have important consequences for chemical evolution models of the halo.

The constant $[\text{Zn}/\text{Fe}]$ abundance ratio seen in the Galaxy is not universal: Abundance analyses of QSO absorption line systems show that Zn is enhanced relative to Fe (e.g. Pettini et al 1994, Lu et al 1996). Although the observed enhancements of the $[\text{Zn}/\text{Cr}]$ ratios may indicate that the gas has been affected by dust depletion, if this were the case, then one would also expect to find large $[\text{S}/\text{Cr}]$ ratios, which are not found. Thus the enhanced Zn abundance in QSO absorption line systems may have a nucleosynthesis origin.

Besides Zn, the abundance ratios of Sc, V, and Ni relative to Fe seem to scale with $[\text{Fe}/\text{H}]$. It should be noted that Zhao & Magain (1989, 1990) claimed a mean $+0.27$ -dex enhancement of $[\text{Sc}/\text{Fe}]$ in metal-poor dwarfs. However, high quality data of Gratton & Sneden (1991) and Peterson et al (1990), as well as the results of McWilliam et al (1995b) found no evidence for a deviation from $[\text{Sc}/\text{Fe}] = 0.0$ in metal-poor giant stars. The lower quality data of Gilroy et al (1988) actually indicated a deficiency of ~ 0.2 dex.

Luck & Bond (1985) claimed enhanced $[\text{Ni}/\text{Fe}]$ ratios in metal-poor stars, and Pilachowski et al (1996) found a mean $[\text{Ni}/\text{Fe}] = -0.27$ near $[\text{Fe}/\text{H}] = -2$; however, other studies tended to find solar $[\text{Ni}/\text{Fe}]$ ratios everywhere. In particular, Peterson et al (1990) demonstrated that the Luck & Bond Ni overabundances were probably the result of selecting lines enhanced above the detection threshold by noise-spikes. The combined studies of Gratton & Sneden (1991), Peterson et al (1990), Edvardsson et al (1993), McWilliam et al (1995a), and Ryan et al (1996) are inconsistent with $[\text{Ni}/\text{Fe}]$ more than ± 0.1 dex from the solar ratio in the interval $-4 \leq [\text{Fe}/\text{H}] \leq 0$; although some of the Gratton & Sneden points are subsolar near $[\text{Fe}/\text{H}] = -2.5$.

Until recently, $[\text{Co}/\text{Fe}]$ and $[\text{Cr}/\text{Fe}]$ ratios were commonly accepted to be independent of $[\text{Fe}/\text{H}]$; however, McWilliam et al (1995b) showed that Co and Cr deviate from a plateau at metallicities below $[\text{Fe}/\text{H}] \sim -2.5$ (see Figure 12). McWilliam et al (1995a) found evidence supporting their results in the data of Gratton & Sneden (1991), Ryan et al (1991), and Wallerstein et al (1963); these trends for Co, Cr, and Mn have subsequently been verified by Ryan et al (1996).

The divergence of $[\text{Co}/\text{Fe}]$, $[\text{Mn}/\text{Fe}]$, and $[\text{Cr}/\text{Fe}]$ (and the heavy elements) from a plateau, below $[\text{Fe}/\text{H}] \sim -2.5$, suggests that chemical evolution was very different below the lowest globular cluster metallicities, perhaps indicating

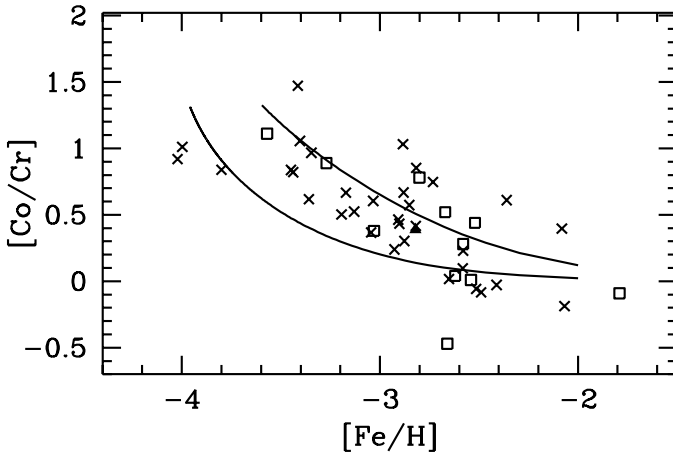


Figure 13 $[\text{Co/Cr}]$ versus $[\text{Fe/H}]$ for extremely metal-poor halo stars: crosses from McWilliam et al (1995), open boxes from Ryan et al (1991). The lines trace the resultant $[\text{Co/Cr}]$ ratios when solar-composition material is mixed with primordial material, characterized by a large $[\text{Co/Cr}]$ value near +1.3 dex.

the existence of population III or early population II stars. If SN II were the dominant source of iron-peak elements at low metallicity, the observed range in $[\text{M/Fe}]$ ratios indicates the minimum range of yield ratios for SN II.

McWilliam et al (1995b, 1996) argued that because the $[\text{Co/Fe}]$, $[\text{Mn/Fe}]$, $[\text{Cr/Fe}]$, and heavy element/Fe ratios differ from the solar values, the metal-poor stars below $[\text{Fe/H}] \sim -2.5$ cannot be the products of simple dilution of higher metallicity gas (e.g. typical of globular cluster composition) by gas with zero metallicity. If metal-poor stars below -2.5 were products of dilution with pure hydrogen, then solar $[\text{Co/Cr}]$ ratios would exist down to -4 . In Figure 13, the tight correlation between $[\text{Co/Cr}]$ and $[\text{Fe/H}]$ sets tight constraints on the dispersion in dilution by zero metallicity gas that might have occurred, i.e. dilution with zero metal gas could not have differed from one star forming region to another by more than a factor of 2 because the $[\text{Fe/H}]$ dispersion at fixed $[\text{Co/Cr}]$ value is ~ 0.3 dex.

It would be interesting to understand why the $[\text{Co/Cr}]$ ratios of extremely metal-poor stars are so tightly correlated with $[\text{Fe/H}]$, whereas for the same stars, the heavy elements show such a large dispersion (Figure 9).

McWilliam et al (1995b) suggested that the heavy elements are produced in large amounts by a rare subclass of SN event and essentially not at all in most events. The tight correlation of $[\text{Co/Cr}]$ with $[\text{Fe/H}]$ might suggest that all or most SN produce iron-peak elements, like Cr, Mn, and Co, in similar

proportions but with metallicity-dependent yields. One possibility suggested by McWilliam et al (1995b) is that the observed $[\text{Co}/\text{Cr}]$ trend in Figure 13 could have occurred if the star-forming gas was in a process of steady chemical enrichment, with several generations of SN gradually enriching the parent cloud in the range $-4 \leq [\text{Fe}/\text{H}] \leq -2.5$. In this model, different kinds of SN II existed with different $[\text{Co}/\text{Cr}]$ yield ratios, and as metallicity increased, the average SN II changed in character until, when metallicity reached $[\text{Fe}/\text{H}] \sim -2.5$, the average SN produced solar $[\text{Co}/\text{Cr}]$ yield ratios.

One way for the metallicity-modulated $[\text{Co}/\text{Cr}]$ yields to occur may be by affecting the mean SN progenitor mass. For example, Wolfire & Cassinelli (1987), Yoshii & Saio (1986), and Kahn (1974) predicted that the IMF is weighted to higher mass stars at low metallicity. Another potential method of altering the SN progenitor mass range is through the effect of metallicity-dependent mass loss; for example, theoretical models by Bowen & Willson (1991) suggested that AGB stars with an initial mass of $2.4 M_{\odot}$ reached the Chandrasekhar mass before the envelope could be ejected.

The observed $[\text{Co}/\text{Cr}]$ versus $[\text{Fe}/\text{H}]$ relation in Figure 13 cannot be explained by the time delay between SN II progenitors with different mass, for the following reason: Any time delay must be less than the maximum SN II progenitor lifetime, which, at 20×10^6 years, is much shorter than the dynamical time scale of the Galaxy; thus chemical evolution in the first 20×10^6 years must have taken place in isolated regions. The observed range of $[\text{Fe}/\text{H}]$ at a fixed $[\text{Co}/\text{Cr}]$ in Figure 13 excludes a range of SFR more than a factor of 2, which conflicts with the fact that SFR are known to vary by orders of magnitude.

Ryan et al (1996) suggested that the SN II $[\text{Co}/\text{Cr}]$ yield is a function of the SN energy and that the SN energy dictates how much dilution of the ejecta occurs and, therefore, the metallicity of the next generation of stars. In this way the observed tight correlation between $[\text{Co}/\text{Cr}]$ and $[\text{Fe}/\text{H}]$ can occur.

An alternative mechanism (L Searle & A McWilliam, in preparation) is that there was a primordial composition, characterized by high $[\text{Co}/\text{Cr}]$, and that this was later diluted with solar composition SN ejecta. In this model, the first generation SN, presumably zero-metallicity population III stars, produced high $[\text{Co}/\text{Cr}]$ ratios, but all subsequent SN II produced solar $[\text{Co}/\text{Cr}]$ yield ratios. Figure 13, shows two “dilution” curves that follow the combined composition of primordial plus solar mix material, with increasing amounts of solar composition material. It is clear that both dilution curves fit some but not all of the observed data points, which may suggest that the putative primordial material was characterized by a spread in metallicity as well as a high $[\text{Co}/\text{Cr}]$ ratio, near +1 dex.

This mechanism produces a tight correlation of $[\text{Co}/\text{Cr}]$ with $[\text{Fe}/\text{H}]$, even with single SN events; thus it fits into the model of discrete chemical enrichment

used by Searle & McWilliam to explain the observed heavy element dispersion. This model implies that stars with $[\text{Fe}/\text{H}] \leq -3.3$ may be the products of individual SN events.

The mechanisms proposed by Ryan et al (1996) and Searle & McWilliam are roughly consistent with the predictions of Audouze & Silk (1995), who considered the physics of mixing of SN ejecta and concluded that there must be a minimum possible metallicity, near $[\text{Fe}/\text{H}] = -4$.

An unusual kind of variation in iron-peak elements was found for the star CS22949-037 by McWilliam et al (1995b): The elements outside the range from Ti to Ni (i.e. C, Na, Mg, Al, Si, Ca, Sc, Sr, Ba) appear to be overabundant by typically ~ 1 dex. The elements within the range Ti to Ni exhibit normal relative ratios. McWilliam et al (1995b) suggest that a simple explanation is that this star is actually deficient in the iron-peak elements. This observation suggests that SN exist that produce relatively small iron-peak yields. Ryan et al (1996) have found two more stars, CS 22876-032 and CS 22897-008, that show unusual chemical compositions, which are indicative of star-to-star scatter and a dispersion in element yields. These star-to-star variations indicate that at low metallicity, the intrinsic dispersion in SN yields can produce anomalous stellar compositions because the averaging process of combining yields from many SN is not yet complete.

FINAL THOUGHTS

One of the themes of this article has been the idea that chemical composition is a function of Galactic environment. In order to learn how environmental parameters can affect chemical evolution, we must make accurate measurements of elemental abundances in all the accessible locations. The different components of our Galaxy are excellent places to make such detailed studies and will ultimately provide us with the means to interpret lower resolution, lower S/N spectra of external galaxies. Chemical analysis of stars in local group galaxies will also be of great use in this regard; in particular, the red giant branch stars permit us to sample the whole history of a stellar system.

The new large telescopes and efficient spectrographs will be of immense help for measuring the composition of the red giants at the distance of the local group galaxies. However, telescope aperture and spectrograph efficiency alone will not be enough to meet this task; we must also make routine the ability to measure chemical abundances from noisy spectra. For elements with many lines, one can derive abundances from noisy spectra by combining several line regions to produce an average line profile of high S/N. When abundances for elements with few lines are required, an average abundance can be measured by combining noisy spectra from many stars, which are acquired with a fiber

spectrograph. Such methods will be commonplace in the future but have already been demonstrated in the works of Jones et al (1995), Carney et al (1987), and Pilachowski & Armandroff (1996).

I cannot stress enough the importance of accurate abundance measurement and reliable estimates of measurement uncertainty: If you don't have accurate measurements, or if you don't know how accurate your measurements are, you cannot draw reliable conclusions. In this regard, large surveys, as exemplified by Edvardsson et al (1993), are particularly useful; for large samples of homogeneous, high quality data with identical analysis, the zero-point uncertainties are reduced.

In the near future, the study of the composition of local group dwarf spheroidal galaxies (dSphs) will be particularly fruitful. These low-mass systems have experienced relatively low rates of chemical evolution, frequently with mean metallicities near $[\text{Fe}/\text{H}] = -2$; as such, these systems may contain a large fraction of stars from the first stellar generations. The low average metallicity of the dSphs and the large numbers of stars in a small area of sky offer the opportunity to make efficient searches for extremely low metallicity stars; we could learn whether a lower limit to metallicity really does exist, as predicted by Audouze & Silk (1995), and how the IMF is affected by metallicity. With more extremely low metallicity stars, we could accumulate additional evidence for composition dispersion at low metallicity and perhaps measure SN element yields, and we also might find more stars with super-enhanced r-process abundances, which are useful for measuring the age of the Galaxy. Furthermore, the observed populations in dSphs, which are indicative of star formation bursts (e.g. Smecker-Hane et al 1994), can be used to measure an approximate time scale for SN Ia.

In the bulge, the oxygen and carbon abundances are desperately needed and might best be measured with infrared spectra of OH and CO lines. Confirmation is required for the low abundances of Si and Ca relative to Mg and Ti in the bulge. The heavy element abundance pattern in the bulge offers a probe of the importance of SN II; thus, measurements of Eu and Ba abundance as a function of metallicity would be useful. The trend of carbon abundance with metallicity must be resolved for the halo. For the extant stars with metallicity in the range $-4 \leq [\text{Fe}/\text{H}] \leq -2$, improved limits on the dispersion of Co, Cr, and Mn abundances with metallicity would test the primordial enrichment model suggested by Searle & McWilliam. Also in this metallicity range, heavy element abundances for a large sample of stars would test the idea that discrete enrichment events, by individual SN, are responsible for the observed dispersion. Abundances of C, N, O, Na, Mg, and Al for main-sequence stars in globular clusters would provide important evidence for or against the role of primordial abundance dispersion in globular clusters. In the Galactic disk,

improved measurements of stellar metallicity towards the Galactic center and anti-center would be useful for understanding the radial metallicity gradient, both present and past. An extensive study of the composition of stars in star-forming regions, similar to the work of Cunha & Lambert (1994), will provide direct information on chemical enrichment and SN yields. It would also be nice to see the experts agree on whether there is a mean age-metallicity relation (AMR) in the solar neighborhood, what fraction of the halo heavy elements were made in the s-process, and the value of the solar iron abundance.

ACKNOWLEDGMENTS

This work would not have been possible without the support of the Observatories of the Carnegie Institution of Washington. I would like to thank the many colleagues who have taught me a few things over the years and helped me on my way; they are Olin Eggen, David Lambert, George Preston, Mike Rich, Allan Sandage, and Leonard Searle. I'd also like to express my deep appreciation to my wife, Kim, who helped with figure preparations, kept me happy, and encouraged me to finish this manuscript.

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Literature Cited

- Abia C, Rebolo R. 1989. *Ap. J.* 347:186–94
- Aller LH, Greenstein JL. 1960. *Ap. J. Suppl.* 5:139–86
- Anders E, Grevesse N. 1989. *Geochim. Cosmochim. Acta* 53:197–214
- Anders E, Zinner E. 1993. *Meteoritics* 28:490–514
- Andersson H, Edvardsson B. 1994. *Astron. Astrophys.* 290:590–98
- Anstee SD, O'Mara JO, Ross JE. 1997. *MNRAS* 284:202–12
- Armosky BJ, Sneden C, Langer GE, Kraft RP. 1994. *Astron. J.* 108:1364–74
- Arnett WD. 1971. *Ap. J.* 166:153–73
- Arnett WD. 1978. *Ap. J.* 219:1008–16
- Arnett WD. 1991. In *Frontiers of Stellar Evolution*, ed. D Lambert, APS Conf. Ser. 20:389–401
- Arp H. 1962. In *Problems in Extragalactic Research*, ed. GC McVittie, IAU Symp. 15:42–47. New York: MacMillan
- Arpigny C, Magain P. 1983. *Astron. Astrophys.* 127:L7–L9
- Audouze J, Silk J. 1995. *Ap. J.* 451:L49–L52
- Audouze J, Tinsley BM. 1976. *Annu. Rev. Astron. Astrophys.* 14:43–79
- Balachandran SC. 1996. In *Cosmic Abundances*, ASP Conf. Ser. 99:188–95
- Balachandran SC, Carney BW. 1996. *Astron. J.* 111:946–61
- Baraffe I, Takahashi K. 1993. *Astron. Astrophys.* 280:476–85
- Barbuy B. 1988. *Astron. Astrophys.* 191:121–27
- Barbuy B, Spite F, Spite M. 1985. *Astron. Astrophys.* 144:343–54
- Bard A, Kock A, Kock M. 1991. *Astron. Astrophys.* 248:315–22
- Bazan G, Mathews GJ. 1990. *Ap. J.* 354:644–48
- Bazan G, Sneden C, Yoss K. 1996. In *Formation of the Galactic Halo... Inside and Out*, ed. H Morrison, A Sarajedini. ASP Conf. Ser. 92:351–54
- Bell RA, Ericksson K, Gustafsson B, Nordlund A. 1976. *Astron. Astrophys. Suppl.* 23:37–95
- Beers TC, Preston GW, Shectman SA. 1985. *Astron. J.* 90:2089–102
- Beers TC, Preston GW, Shectman SA. 1992.

- Astron. J.* 103:1987–2034
- Beers TC, Sommer-Larsen J. 1995. *Ap. J. Suppl.* 96:175–221
- Bessell MS, Norris J. 1984. *Ap. J.* 285:622–36
- Bessell MS, Sutherland RS, Ruan K. 1991. *Ap. J.* 383:L71–L74
- Biémont E, Bardoux M, Kurucz RL, Ansbacher W, Pinnington EH. 1991. *Astron. Astrophys.* 249:539–44
- Blaauw A. 1991. In *The Physics of Star Formation and Early Stellar Evolution*, ed. CJ Lada, ND Kylafis, pp. 125–54. NATO ASI Series. Dordrecht: Kluwer
- Blackwell DE, Booth AJ, Haddock DJ, Petford AD, Leggett SK. 1986. *MNRAS* 220:549–53
- Blackwell DE, Booth AJ, Petford AD. 1984. *Astron. Astrophys.* 132:236–39
- Blackwell DE, Lynas-Gray AE, Smith G. 1995. *Astron. Astrophys.* 296:217–32
- Bond HE. 1981. *Ap. J.* 248:606–11
- Boothroyd AJ, Sackmann IJ, Wasserburg GJ. 1994. *Ap. J.* 430:L77–L80
- Bowen GH, Willson LA. 1991. *Ap. J.* 375:L53–L56
- Branch D, Bonnell J, Tomkin J. 1978. *Ap. J.* 225:902–7
- Briley MM, Hesser JE, Bell RA. 1991. *Ap. J.* 373:482–96
- Briley MM, Smith VV, Suntzeff NB, Lambert DL, Bell RA, Hesser JE. 1996. *Nature* 383:604–6
- Brown JA, Sneden C, Lambert DL, Dutchover E Jr. 1989. *Ap. J. Suppl.* 71:293–322
- Brown JA, Wallerstein G. 1992. *Astron. J.* 104:1818–30
- Brown JA, Wallerstein G, Zucker D. 1996. In *Formation of the Galactic Halo... Inside and Out*, ed. H Morrison, A Sarajedini, ASP Conf. Ser. 92:355–58
- Burbidge EM, Burbidge GR, Fowler WA, Hoyle F. 1957. *Rev. Mod. Phys.* 29:547–650
- Busso M, Lambert DL, Beglio L, Gallino R, Raiteri CM, Smith VV. 1995. *Ap. J.* 446:775–92
- Butcher HR. 1975. *Ap. J.* 199:710–17
- Butcher HR. 1987. *Nature* 328:127–31
- Carbon DF, Barbuy B, Kraft RP, Friel ED, Suntzeff NB. 1987. *Publ. Astron. Soc. Pac.* 99:335–68
- Carney BW, Latham DW, Laird JB. 1990. In *ESO/CTIO Workshop on Bulges of Galaxies*, ed. BJ Jarvis, DM Terndrup, 35:127–34. Garching: Eur. South. Obs.
- Carney BW, Laird JB, Latham DW, Kurucz RL. 1987. *Astron. J.* 94:1066–76
- Castro S, Rich RM, Grenon M, McCarthy JK. 1997. In press
- Castro S, Rich RM, McWilliam A, Ho LC, Spinrad H, et al. 1996. *Astron. J.* 111:2439–52
- Cayrel R. 1987. In *ESO Workshop on Stellar Evolution and Dynamics in the Outer Halo of the Galaxy*, pp. 627–35. Garching: Eur. South. Obs.
- Clayton DD. 1985. *Ap. J.* 288:569–74
- Clayton DD. 1988. *MNRAS* 234:1–36
- Clegg RES, Lambert DL, Tomkin J. 1981. *Ap. J.* 250:262–75
- Conti PS, Greenstein JL, Spinrad H, Wallerstein G, Vardya MS. 1967. *Ap. J.* 148:105–27
- Corliss CH, Bozman WR. 1962. *NBS Monog.* No. 53
- Cowan JJ, Burris DL, Sneden C, McWilliam A, Preston GW. 1995. *Ap. J.* 439:L51–L54
- Cowan JJ, McWilliam A, Sneden C, Burris DL. 1997. *Ap. J.* In press
- Cowan JJ, Sneden C, Truran JW, Burris DL. 1996. *Ap. J.* 460:L115–18
- Cunha K, Lambert DL. 1992. *Ap. J.* 399:586–98
- Cunha K, Lambert DL. 1994. *Ap. J.* 426:170–91
- Denisenkov PA, Denisenkova SN. 1990. *Sov. Astron. Lett.* 16:642–51
- Edmunds MG. 1975. *Astrophys. Space Sci.* 32:483–91
- Edmunds MG, Greenhow RM, Johnson D, Klückers V, Vila BM. 1991. *MNRAS* 251:33P–36P
- Edvardsson B, Andersen J, Gustafsson B, Lambert DL, Nissen PE, Tomkin J. 1993. *Astron. Astrophys.* 275:101–52
- Eggen OJ, Sandage A. 1969. *Ap. J.* 158:669–84
- Feltzing S. 1995. PhD thesis. Univ. Uppsala, Sweden
- François P. 1986. *Astron. Astrophys.* 160:264–76
- François P. 1987. *Astron. Astrophys.* 176:294–98
- François P. 1988. *Astron. Astrophys.* 195:226–29
- François P. 1991. *Astron. Astrophys.* 247:56–63
- François P. 1996. *Astron. Astrophys.* 313:229–33
- François P, Matteucci F. 1993. *Astron. Astrophys.* 280:136–40
- Friel ED. 1995. *Annu. Rev. Astron. Astrophys.* 33:381–414
- Friel ED, Boesgard AM. 1992. *Ap. J.* 387:170–80
- Friel ED, Janes KA. 1993. *Astron. Astrophys.* 267:75–91
- Frogel JA, Whitford AE. 1987. *Ap. J.* 320:199–237
- Fuhrmann K, Axer M, Gehren T. 1995. *Astron. Astrophys.* 301:492–500
- Geisler D. 1987. *Astron. J.* 94:84–91
- Geisler D, Claria JJ, Miniti D. 1992. *Astron. J.* 104:1892–905
- Geisler D, Friel E. 1992. *Astron. J.* 104:128–43
- Gilmore G. 1984. *MNRAS* 207:223–40
- Gilmore G, Reid N. 1983. *MNRAS* 202:1025–47
- Gilmore G, Wyse RFG. 1985. *Astron. J.* 90:2015–26

- Gilmore G, Wyse RFG. 1986. *Nature* 322:806–7
- Gilroy KK, Sneden C, Pilachowski CA, Cowan JJ. 1988. *Ap. J.* 327:298–320
- Gorgas J, Faber SM, Burstein D, Gonzalez J, Courteau S, Prosser C. 1993. *Ap. J. Suppl.* 86:153–98
- Gratton RG. 1989. *Astron. Astrophys.* 208:171–78
- Gratton RG. 1994. In *Nuclei in the Cosmos*, 3:3–17. ed. M Busso, R Gallino, CM Raiteri. New York: Am. Inst. Phys.
- Gratton RG, Sneden C. 1987. *Astron. Astrophys.* 178:179–93
- Gratton RG, Sneden C. 1988. *Astron. Astrophys.* 204:193–218
- Gratton RG, Sneden C. 1990. *Astron. Astrophys.* 234:366–86
- Gratton RG, Sneden C. 1991. *Astron. Astrophys.* 241:501–25
- Gratton RG, Sneden C. 1994. *Astron. Astrophys.* 287:927–46
- Grenon M. 1987. *J. Astrophys. Astron.* 8:123–39
- Grenon M. 1989. *Astrophys. Space Sci.* 156:29–37
- Grevesse N, Noels A. 1993. *Phys. Scripta* T47:133–38
- Griffin R, Griffin R, Gustafsson B, Vieira T. 1982. *MNRAS* 198:637–58
- Gustafsson B, Kjaergaard P, Andersen S. 1974. *Astron. Astrophys.* 34:99–128
- Hartquist TW, Cameron AGW. 1977. *Astrophys. Space Sci.* 48:145–58
- Hartwick FDA. 1976. *Ap. J.* 209:418–23
- Helfer HL, Wallerstein G. 1968. *Ap. J. Suppl.* 16:1–47
- Holweger H, Muller EA. 1974. *Solar phys.* 39:19–30
- Holweger H, Bard A, Kock A, Kock M. 1991. *Astron. Astrophys.* 249:545–49
- Holweger H, Heise C, Kock M. 1990. *Astron. Astrophys.* 232:510–15
- Holweger H, Kock M, Bard A. 1995. *Astron. Astrophys.* 296:233–40
- Hoyle F. 1954. *Ap. J. Suppl.* 1:121–46
- Huggins PJ, Williams PM. 1974. *MNRAS* 169:1P–5P
- Ibata RA, Gilmore GF, Irwin MJ. 1994. *Nature* 370:194–96
- Iben I Jr. 1975. *Ap. J.* 196:525–47
- Iben I Jr, Truran JW. 1978. *Ap. J.* 220:980–95
- Iben I Jr, Tutukov A. 1984. *Ap. J. Suppl.* 54:335–72
- Idiart TP, de Freitas Pacheco JA, Costa RDD. 1996a. *Astron. J.* 111:1169–74
- Idiart TP, de Freitas Pacheco JA, Costa RDD. 1996b. *Astron. J.* 112:2541–48
- Jønch-Sørensen H. 1995. *Astron. Astrophys.* 298:799–817
- Jones JB, Wyse RFG, Gilmore G. 1995. *Publ. Astron. Soc. Pac.* 107:632–47
- Kahn FD. 1974. *Astron. Astrophys.* 37:149–62
- Käppeler F, Beer H, Wisshak K. 1989. *Rep. Prog. Phys.* 52:945–1013
- King JR. 1993. *Astron. J.* 106:1206–21
- Kipper T, Jorgensen UG, Klochkova VG, Panchuk VE. 1996. *Astron. Astrophys.* 306:489–500
- Knude J. 1990. *Astron. Astrophys.* 230:16–20
- Kostik RI, Shchukina NG, Rutten RJ. 1996. *Astron. Astrophys.* 305:325–42
- Kraft RP. 1994. *Publ. Astron. Soc. Pac.* 106:553–65
- Kraft RP, Sneden C, Langer GE, Prosser CF. 1992. *Astron. J.* 104:645–68
- Kraft RP, Suntzeff NB, Langer GE, Carbon DF, Trefzger CF, et al. 1982. *Publ. Astron. Soc. Pac.* 94:55–66
- Kraft RP, et al. 1997. *Astron. J.* 113:279–95
- Laird J. 1985. *Ap. J.* 289:556–69
- Laird J, Rupen MP, Carney B, Latham D. 1988. *Astron. J.* 96:1908–17
- Lambert DL. 1987. *J. Astrophys. Astron.* 8:103–22
- Lambert DL, Heath JE, Lemke M, Drake J. 1995a. *Ap. J. Suppl.* 103:183–210
- Lambert DL, Ries LM. 1981. *Ap. J.* 248:228–48
- Lambert DL, Smith VV, Busso M, Gallino R, Straniero O. 1995b. *Ap. J.* 450:302–17
- Larson RB. 1974. *MNRAS* 166:585–616
- Larson RB. 1976. *MNRAS* 176:31–52
- Lu L, Sargent WLW, Barlow TA, Churchill CW, Vogt SS. 1996. *Ap. J. Suppl.* 107:475–519
- Luck RE, Bond HE. 1981. *Ap. J.* 244:919–37
- Luck RE, Bond HE. 1985. *Ap. J.* 292:559–77
- Luck RE, Challener SL. 1995. *Astron. J.* 110:2968–3009
- Lynden-Bell D. 1975. *Vistas Astron.* 19:299–316
- Maeder A. 1991. *Q. J. R. Astron. Soc.* 32:217–31
- Magain P. 1987. *Astron. Astrophys.* 179:176–80
- Magain P. 1989. *Astron. Astrophys.* 209:211–25
- Magain P. 1995. *Astron. Astrophys.* 297:686–94
- Majewski SR. 1993. *Annu. Rev. Astron. Astrophys.* 31:575–638
- Mathews GJ, Bazan G, Cowan JJ. 1992. *Ap. J.* 391:719–35
- Mathews GJ, Cowan JJ. 1990. *Nature* 345:491–94
- Matteucci F, Brocato E. 1990. *Ap. J.* 365:539–43
- Matteucci F, François P. 1989. *MNRAS* 239:885–904
- Matteucci F, François P. 1992. *Astron. Astrophys.* 262:L1–L4
- Matteucci F, Raiteri CM, Busso M, Gallino R, Gratton R. 1993. *Astron. Astrophys.* 272:421–29
- McClure RD. 1984. *Publ. Astron. Soc. Pac.* 96:117–27

- McWilliam A. 1990. *Ap. J. Suppl.* 1075–128
- McWilliam A, Geisler D, Rich RM. 1992. *Publ. Astron. Soc. Pac.* 104:1193–204
- McWilliam A, Preston GW, Sneden C, Searle L. 1995a. *Astron. J.* 109:2757–99
- McWilliam A, Preston GW, Sneden C, Searle L, Shectman S. 1996. In *Formation of the Galactic Halo . . . Inside and Out*, ed. H Morrison, A Sarajedini, ASP Conf. Ser. 92:317–26
- McWilliam A, Preston GW, Sneden C, Shectman S. 1995b. *Astron. J.* 109:2736–56
- McWilliam A, Rich RM. 1994. *Ap. J. Suppl.* 91:749–91
- Meusinger H, Reimann H-G, Stecklum B. 1991. *Astron. Astrophys.* 245:57–74
- Meyer BS. 1994. *Annu. Rev. Astron. Astrophys.* 32:153–90
- Meyer BS, Mathews GJ, Howard WM, Woosley SE, Hoffman RD. 1992. *Ap. J.* 399:656–64
- Milford PN, O'Mara BJ, Ross JE. 1994. *Astron. Astrophys.* 292:276–80
- Montgomery KA, Janes KA, Phelps RL. 1994. *Astron. J.* 108:585–93
- Nissen PE, Edvardsson B. 1992. *Astron. Astrophys.* 261:255–62
- Nissen PE, Gustafsson B, Edvardsson B, Gilmore G. 1994. *Astron. Astrophys.* 285:440–50
- Nissen PE, Schuster WJ. 1991. *Astron. Astrophys.* 251:457–68
- Nomoto K, Thielemann FK, Yokio Y. 1984. *Ap. J.* 286:644–58
- Norris J, Ryan S. 1989. *Ap. J.* 340:739–61
- Norris J, Ryan S. 1991. *Ap. J.* 380:403–18
- Norris JE, Da Costa GS. 1995. *Ap. J.* 447:680–705
- Norris JE, Freeman KC, Mighell KJ. 1996. *Ap. J.* 462:241–254
- Norris JE, Peterson RC, Beers TC. 1993. *Ap. J.* 415:797–810
- Ostriker JP, Thuan TX. 1975. *Ap. J.* 202:353–64
- Pagel BEJ. 1968. In *Origin and Distribution of the Elements*, ed. LH Ahrens, pp. 195–204. Oxford: Pergamon
- Pagel BEJ. 1989. In *Evolutionary Phenomena in Galaxies*, ed. JE Beckman, BEJ Pagel, pp. 201–23. Cambridge: Cambridge Univ. Press
- Pagel BEJ, Patchett BE. 1975. *MNRAS* 172:13–40
- Pagel BEJ, Tautvaisiene G. 1995. *MNRAS* 276:505–14
- Pauls U, Grevesse N, Huber MCE. 1990. *Astron. Astrophys.* 231:536–42
- Peterson RC, Green EM. 1995. *BAAS* 187: #107.06
- Peterson RC, Kurucz RL, Carney BW. 1990. *Ap. J.* 350:173–85
- Peterson RC, Sneden C. 1978. *Ap. J.* 225:913–18
- Pettini M, Smith LJ, Hunstead RW, King DL. 1994. *Ap. J.* 426:79–96
- Pilachowski CA, Armandroff TE. 1996. *Astron. J.* 111:1175–83
- Pilachowski CA, Sneden C, Kraft RP. 1996. *Astron. J.* 111:1689–704
- Pilachowski CA, Sneden C, Wallerstein G. 1983. *Ap. J. Suppl.* 52:241–87
- Pilyugin LS, Edmunds MG. 1996a. *Astron. Astrophys.* 313:783–91
- Pilyugin LS, Edmunds MG. 1996b. *Astron. Astrophys.* 313:792–802
- Raiteri CM, Busso M, Picchio G, Gallino R, Pulone L. 1991. *Ap. J.* 367:228–38
- Raiteri CM, Gallino R, Busso M. 1992. *Astron. Astrophys.* 387:263–75
- Raiteri CM, Gallino R, Busso M, Neuberger D, Käppeler F. 1993. *Ap. J.* 419:207–23
- Raiteri CM, Villata M, Navarro JF. 1996. *Astron. Astrophys.* 315:105–15
- Reeves H. 1972. *Astron. Astrophys.* 19:215–23
- Renzini A, Voli M. 1981. *Astron. Astrophys.* 94:175–93
- Rich RM. 1988. *Astron. J.* 95:828–65
- Rich RM. 1990. *Ap. J.* 362:604–19
- Ross JE, Aller LH. 1976. *Science* 191:1223–29
- Ryan SG, Norris JE. 1991. *Astron. J.* 101:1865–78
- Ryan SG, Norris JE, Beers TC. 1996. *Ap. J.* 471:254–78
- Sadler EM, Rich RM, Terndrup DM. 1996. *Astron. J.* 112:171–85
- Sandage A. 1969. *Ap. J.* 158:1115–36
- Sandage A. 1987. *Astron. J.* 93:610–15
- Sandage A, Fouts G. 1987. *Astron. J.* 93:74–115
- Scalo JM. 1987. In *Starbursts and Galaxy Evolution, Proc. Moriond Astrophys. Meet.*, ed. TX Thuan, T Montmerle, J Tran Thanh Van. 22:445–465
- Schmidt M. 1963. *Ap. J.* 137:758–69
- Searle L, Sargent WLW. 1972. *Ap. J.* 173:25–33
- Searle L, Zinn R. 1978. *Ap. J.* 225:357–79
- Seeger PA, Fowler WA, Clayton DD. 1965. *Ap. J. Suppl.* 11:121–66
- Shetrone MD. 1996a. *Astron. J.* 112:1517–35
- Shetrone MD. 1996b. *Astron. J.* 112:2639–49
- Smecker-Hane T, Stetson PB, Hesser JE, Lehnert MD. 1994. *Astron. J.* 108:507–13
- Smecker-Hane T, Wyse RFG. 1992. *Astron. J.* 103:1621–26
- Smith VV, Cunha K, Lambert DL. 1995. *Astron. J.* 110:2827–43
- Smith VV, Lambert DL. 1990. *Ap. J. Suppl.* 72:387–416
- Sneden C, Crocker DA. 1988. *Ap. J.* 335:406–14
- Sneden C, Gratton RG, Crocker DA. 1991a. *Astron. Astrophys.* 246:354–67
- Sneden C, Kraft RP, Langer GE. 1991b. *Astron. J.* 102:2001–21
- Sneden C, McWilliam A, Preston GW, Cowan JJ, Burris DL, Armosky BJ. 1996. *Ap. J.* 467:819–40

- Sneden C, Parthasarathy M. 1983. *Ap. J.* 267: 757–78
- Sneden C, Pilachowski CA. 1985. *Ap. J.* 288: L55–L58
- Sneden C, Preston GW, McWilliam A, Searle L. 1994. *Ap. J.* 431:L27–L30
- Sommer-Larsen J. 1991. *MNRAS* 250:356–62
- Spiesman WJ. 1992. *Ap. J.* 397:L103–5
- Spinrad H, Taylor BJ. 1969. *Ap. J.* 157:1279–340
- Spite M. 1992. In *The Stellar Populations of Galaxies*, ed. B Barbuy, A Renzini. IAU Symp. 149:123–32
- Spite M, Spite F. 1978. *Astron. Astrophys.* 67: 23–31
- Spite M, Spite F. 1979. *Astron. Astrophys.* 76: 150–57
- Spite M, Spite F. 1980. *Astron. Astrophys.* 89: 118–22
- Spite M, Spite F. 1991. *Astron. Astrophys.* 252: 689–92
- Suntzeff NB. 1989. In *The Abundance Spread Within Globular Clusters*, ed. M Cayrel de Strobel, M Spite, T Lloyd Evans, pp. 71–81. Paris: Obs. Paris
- Taylor BJ. 1996. *Ap. J. Suppl.* 102:105–28
- Terndrup DM, Frogel JA, Whitford AE. 1991. *Ap. J.* 378:742–55
- Terndrup DM, Sadler EM, Rich RM. 1995. *Astron. J.* 110:1774–92
- Thielemann FK, Nomoto K, Yokio Y. 1986. *Astron. Astrophys.* 158:17–33
- Timmes FX, Woosley SE, Weaver TA. 1995. *Ap. J. Suppl.* 98:617–58
- Tinsley BM. 1979. *Ap. J.* 229:1046–56
- Tomkin J, Lambert DL, Balachandran S. 1985. *Ap. J.* 290:289–95
- Tomkin J, Lemke M, Lambert DL, Sneden C. 1992. *Astron. J.* 104:1568–84
- Tomkin J, Sneden C, Lambert DL. 1986. *Ap. J.* 302:415–20
- Tomkin J, Woolf VM, Lambert DL. 1995. *Astron. J.* 109:2204–17
- Tosi M. 1988. *Astron. Astrophys.* 197:47–51
- Tripicco MJ, Bell RA, Dorman B, Hufnagel B. 1995. *Astron. J.* 109:1697–705
- Truran JW. 1981. *Astron. Astrophys.* 97:391–93
- Truran JW, Cameron AGW. 1971. *Astrophys. Space. Sci.* 14:179–222
- Truran JW, Iben I Jr. 1977. *Ap. J.* 216:797–810
- Twarog BA. 1980. *Ap. J.* 242:242–59
- Uehara H, Susa H, Nishi R, Yamada M, Nakamura T. 1996. *Ap. J. Lett.* 473:95–98
- van den Bergh S. 1962. *Astron. J.* 67:486–90
- Vanture A. 1992. *Astron. J.* 104:1997–2004
- Vanture A. 1993. *Publ. Astron. Soc. Pac.* 105:445
- Vanture AD, Wallerstein G, Brown JA. 1994. *Astron. J.* 106:835–42
- Wasserburg GJ, Boothroyd AI, Sackmann IJ. 1995. *ApJ* 447:L37–L40
- Wallerstein G, Carlson M. 1960. *Ap. J.* 132:276–77
- Wallerstein G. 1962. *Ap. J. Suppl.* 6:407–43
- Wallerstein G, Greenstein JL, Parker R, Helfer HL, Aller LH. 1963. *Ap. J.* 137:280–300
- Wheeler JC, Sneden C, Truran JW. 1989. *Annu. Rev. Astron. Astrophys.* 27:279–349
- White SDM, Audouze J. 1983. *MNRAS* 203:603–18
- Whitford AE, Rich RM. 1983. *Ap. J.* 274:723–32
- Wolfire MG, Cassinelli JP. 1987. *Ap. J.* 319:850–67
- Woolf VM, Tomkin J, Lambert DL. 1995. *Ap. J.* 453:660–72
- Woosley SE, Weaver TA. 1995. *Ap. J. Suppl.* 101:181–235
- Worthey G, Dorman B, Jones LA. 1996. *Astron. J.* 112:948–53
- Worthey G, Faber SM, Gonzalez JJ. 1992. *Ap. J.* 398:69–73
- Wyse RFG, Gilmore G. 1986. *Astron. J.* 91:855–69
- Wyse RFG, Gilmore G. 1991. *Ap. J.* 367:L55–L58
- Wyse RFG, Gilmore G. 1992. *Astron. J.* 104:144–53
- Wyse RFG, Gilmore G. 1995. *Astron. J.* 110:2771–87
- Yoshii Y, Saio H. 1986. *Ap. J.* 301:587–600
- Zhao G, Magain P. 1990. *Astron. Astrophys.* 238:242–48
- Zhao G, Magain P. 1991. *Astron. Astrophys.* 244:425–32
- Zinner E. 1996. In *Cosmic Abundances. ASP Conf. Ser.* 99:147–61