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Globular Clusters and Halo Field Stars

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Abstract

Abundance ratios of representative Fe-peak, α, neutron-capture, and proton-capture elements are gathered together for many globular clusters, several open clusters, and some representative samples of disk and halo stars. Comparisons of these abundances reveal generally very good agreement between clusters and the field, with some notable deviant clusters for each element. These deviations may be due to real abundance differences in a few cases, and in others may signal the need for new abundance analyses. Overall, with the exception of the light proton-capture elements, the element production history of globular clusters appears to be comparable to field stars of similar metallicities.

1.1 Introduction

Globular clusters are the most easily recognized constituents of the Milky Way Galaxy, and often are the only objects that can be detected in the halos of other galaxies. There are only 150 globular clusters listed in the summary catalog of Harris (1996)*, and the total mass contained in the cluster system is roughly only a percent of the mass sum of halo stars not included in clusters (which itself is a percent or less of the total mass of our Galaxy). But halo globular clusters are extremely old, and thus along with old field stars carry vital information on the formation and early chemical history of the Galaxy.

Many of the spectroscopic investigations of globular clusters over the past few decades have concentrated on determinations of reliable metallicity ($\equiv$ [Fe/H]) scales and on attempts to map out the abundance variations among light elements that are vulnerable to alterations from proton-capture fusion reactions in the interiors of low-to-intermediate-mass stars. A recent cluster metallicity scale study has been conducted by Kraft & Ivans (2003, 2004); see their papers for extended discussion and references to previous efforts (e.g., Zinn & West 1984; Carretta & Gratton 1997). Light element abundance variations in globular clusters have been discussed thoroughly several times in the past decade (e.g., Kraft 1994; Sneden 2000; Freeman & Bland-Hawthorn 2002), and will not be featured here.

Less attention has been given to abundance ratios of heavier elements, which usually can only be synthesized in massive stars. A fundamental question of early Galactic evolution has not been satisfactorily addressed to date: were the globular clusters and halo field stars formed from gas that experienced similar chemical enrichments? Are these two stellar groups truly members of the same population, or were they formed from fundamentally

* Available at http://physun.mcmaster.ca/∼harris/WEHarris.html

different interstellar media? Here we will address this question from a purely observational perspective, by comparing relative abundance ratios [X/Fe] in globular clusters and halo field stars. No attempt will be made to examine all observed elements. Instead, representative examples from several element groups will be chosen for comment: (1) nickel and copper from the iron-peak elements, (2) calcium from the α-elements, (3) barium, lanthanum, and europium from the neutron-capture (*n*-capture) elements, and (4) briefly, oxygen, sodium, and aluminum from the proton-capture elements. These have been chosen because their observational uncertainties are relatively small, and they have been studied in a large number of stars in many globular clusters. We will examine trends in these [X/Fe] abundance ratios as functions of [Fe/H] metallicity, plotting the means and standard deviations for each globular cluster but displaying the values for individual stars of the halo field. Obviously anomalous points will be highlighted with the aim of triggering further observational studies to confirm or disprove the aberrations, and new theoretical studies to explain the agreements and disagreements between the chemical compositions of clusters and the halo field.

1.2 Cluster and Field Star Samples

We searched the literature for high-resolution abundance studies of globular clusters, concentrating on the results of the last 10–15 years that have been based on high signal-to-noise ratio spectra obtained with echelle spectrographs. Our selection of studies to be included here includes all of the large-sample ($\gtrsim$5 stars/cluster) investigations and most of the small-sample papers. In Table 1.1 we list the clusters included here, their overall metallicities on a uniform scale derived from Ca II infrared triplet measurements (Kraft & Ivans 2003, 2004)*, the number of stars analyzed per cluster, and the literature sources adopted. We do not pretend that the chosen set is complete, and for clusters that have been subjected to multiple analyses we employed our best judgment as to when to adopt the most recently published abundances and when to include both older and new abundance results. In the abundance plots of this paper, we will employ the cluster metallicities of Table 1.1, but will adopt without change the abundance ratios [X/Fe] reported in the individual papers listed in the table.

Our concentration on the most recent abundance studies of globular cluster stars unfortunately may suggest to the general reader that this subject was developed only in the late 1980s. Here we take proper note of the pioneering early efforts, made with analyses of photographic (thus relatively low signal-to-noise ratio) spectra obtained with typically 2–4 m telescopes beginning in the 1960s. The first detailed chemical composition study of globular cluster giants was that of Helfer, Wallerstein, & Greenstein (1959), who obtained spectra of one giant in each of M13 and M92. Many of their results, such as the metallicity difference between these two clusters, have not been challenged by subsequent investigations. In a series of papers, Cohen (1978, 1979, 1980, 1981) used the newly commissioned echelle spectrographs of the Kitt Peak and Cerro Tololo 4 m telescopes to perform the first systematic studies that allowed intercomparisons of the abundance patterns in several globular clusters. Peterson (1980) essentially introduced the now-familiar study of advanced, high-temperature proton-capture nucleosynthesis in globular clusters with her discovery of

* Kraft & Ivans (2003, 2004) derived their metallicity scale from clusters lying in the abundance range $-2.4 \leq$ [FeII/H] ≤ -0.7. So, for the more metal-rich clusters listed in Table 1.1 we adopt the Carretta et al. (2001) metallicity for NGC 6528 and the Cohen et al. (1999) metallicity for NGC 6553. Also, Pal 5 was not included in the Kraft & Ivans compilation, so we adopt here the value derived by Smith, Sneden, & Kraft (2002).

Table 1.1. *Cluster Metallicities and Abundance References*

NGC (Other)	[Fe/H][a]	No.	Reference
			GLOBULAR CLUSTERS
104 (47 Tuc)	–0.70	4	Brown & Wallerstein (1992)
288	–1.41	13	Shetrone & Keane (2000)
362	–1.34	12	Shetrone & Keane (2000)
1904	–1.64	2	Gratton & Ortolani (1989)
2298	–1.97	3	McWilliam, Geisler, & Rich (1992)
3201	–1.56	18	Gonzalez & Wallerstein (1998),
		6	Covey et al. (2003)
4590 (M68)	–2.43	2	Gratton (1989)
4833	–2.06	2	Gratton (1989)
5272 (M3)	–1.50	23	Sneden et al. (2004)
5897	–2.09	2	Gratton (1987)
5904 (M5)	–1.26	36	Ivans et al. (2001)
		25	Ramírez & Cohen (2003)
6121 (M4)	–1.15	36	Ivans et al. (1999)
6205 (M13)	–1.60	17	Kraft et al. (1997), Sneden et al. (2004)
6254 (M10)	–1.51	14	Kraft et al. (1995)
6287	–2.20	3	Lee & Carney (2002)
6293	–2.00	2	Lee & Carney (2002)
6341 (M92)	–2.38	3	Shetrone (1996)
		29	Sneden et al. (2000a)
6352	–0.78	2	Gratton (1987)
6362	–1.15	2	Gratton (1987)
6397	–2.02	16	Castilho et al. (2000)
6528	+0.07	4	Carretta et al. (2001)
6541	–1.83	2	Lee & Carney (2002)
6553	–0.16	2	Cohen et al. (1999)
		5	Barbuy et al. (1999)
6656 (M22)	–1.71	7	Brown & Wallerstein (1992)
6715 (M54)	–1.47	5	Brown et al. (1999)
6752	–1.57	38	Yong et al. (2003)
6838 (M71)	–0.81	25	Ramírez & Cohen (2002)
7006	–1.48	6	Kraft et al. (1998)
7078 (M15)	–2.42	18	Sneden et al. (1997,2000a)
—- (Pal 5)	–1.28	4	Smith, Sneden, & Kraft (2002)
—- (Pal 12)	–0.95	2	Brown, Wallerstein, & Zucker (1997)
—- (Rup 106)	–1.18	2	Brown, Wallerstein, & Zucker (1997)
			OPEN CLUSTERS
1435 (M45)	+0.06	2	King et al. (2000)
2112	–0.09	2	Brown et al. (1996)
2243	–0.48	2	Gratton & Contarini (1994)
2264	–0.23	4	King et al. (2000)
6705 (M11)	+0.10	10	Gonzalez & Wallerstein (2000)
6819	+0.09	3	Bragaglia et al. (2001)
Mel 66	–0.38	2	Gratton & Contarini (1994)
Mel 71	–0.30	2	Brown et al. (1996)
γ Scl	+0.20	9	Edvardsson et al. (1995)

[a][Fe/H] values are from Kraft & Ivans (2003, 2004), except where noted in the text.

order-of-magnitude sodium abundance variations among red giant stars of M13. And Pilachowski (1984, and references therein) analyzed more globular clusters, extended the same techniques to open clusters, and attempted to assemble the extant data of that era to gain some overall Galactic chemical evolution insights. The current state-of-the-art in globular cluster chemical composition studies owes much to these early works.

For comparison we gathered similar data for some open clusters, although these objects have been studied much less intensively than have globulars, and with usually smaller sample sizes. Table 1.1 lists the representative open clusters employed here; the metallicity values are those of the individual literature surveys.

The field star results emphasize large-sample surveys involving 50–200 stars. For high-metallicity ([Fe/H] $>$ –1) disk stars we adopted the abundances of Reddy et al. (2003), supplemented by some Eu abundances of Woolf, Tomkin, & Lambert (1995) and La abundances of Simmerer et al. (2001, and in preparation). For a wider metallicity range, 0 $\gtrsim$ [Fe/H] $\gtrsim$ –3, we employed the results of Fulbright (2000). And to expand the representation of very metal-poor ([Fe/H] $<$ –2) stars in various plots, we added in data from the smaller samples of Gratton & Sneden (1991), McWilliam et al. (1995), Ryan, Norris, & Beers (1996), Burris et al. (2000), Johnson & Bolte (2001), Carretta et al. (2002), and Johnson (2002). We made no attempt to normalize the results of various studies to each other (for some elements there is little overlap among the studies). The reader is also cautioned that the field-star results often come from analyses of blue-region spectra, while those for globular cluster stars are generally from yellow-red region spectra. This raises concerns about comparing abundance results that have been obtained from different spectral features. Such scale considerations are beyond the scope of this general review but should be pursued in future inquiries.

1.3 Fe-peak Elements: Nickel and Copper

Elements in the atomic number range 21 $\leq$ Z $\leq$ 30 comprise the Fe-peak domain, with the exception of Ti (Z = 22), which is also partially an α-element. Among these elements it is particularly easy to compare abundances of Ni and Fe, both of which have numerous neutral-species lines in most spectral ranges. Most comprehensive analyses of globular cluster stars include determinations of Ni abundances.

In Figure 1.1 we show mean abundances for 28 globular clusters and seven open clusters, with individual abundances for the field star samples described in the preceding sections. The metallicity range displayed in Figure 1.1 and most other figures in this paper is –3.2 $<$ [Fe/H] $<$ +0.3. Field stars certainly are known to exist at lower metallicities. For example, there are four stars in the Carretta et al. (2002) survey and eight stars in the McWilliam et al. (1995) survey with [Fe/H] $\leq$ –3.2. Recent surveys have discovered, or analyzed in detail, new extremely low-metallicity stars (e.g., Christlieb et al. 2002; Spite 2004). However, it is well known that no Galactic globular clusters have [Fe/H] $<$ –2.5; the very metal-poor halo field star domain has no counterpart in the globular cluster system.

The data of Figure 1.1 show that [Ni/Fe] $\approx$ 0.0 in globular clusters, open clusters, and halo field stars. The cluster abundance σ values generally indicate the "quality" of the individual abundance studies: signal-to-noise ratio and resolution of the spectra, stellar sample sizes, and number of lines contributing to a given elemental abundance. No evidence to date can be found for true star-to-star [Ni/Fe] variations in any cluster.

Several clusters possess apparently subsolar Ni abundances: [Ni/Fe] $\approx$ –0.3. Two of the clusters, Pal 12 and Rup 106, are globulars that are unusual in several respects: (1) they are outer-halo clusters with galactocentric distances larger than most other clusters of Table 1.1; (2) their color-magnitude diagrams indicate ages younger by a few Gyr than typical globulars; and (3) they have abnormally low relative abundances of α-elements (see next section). The low [Ni/Fe] ratios of Pal 12 and Rup 106 may well be real, but there have only been abundance analyses of two (faint) stars in each of these two clusters (Brown

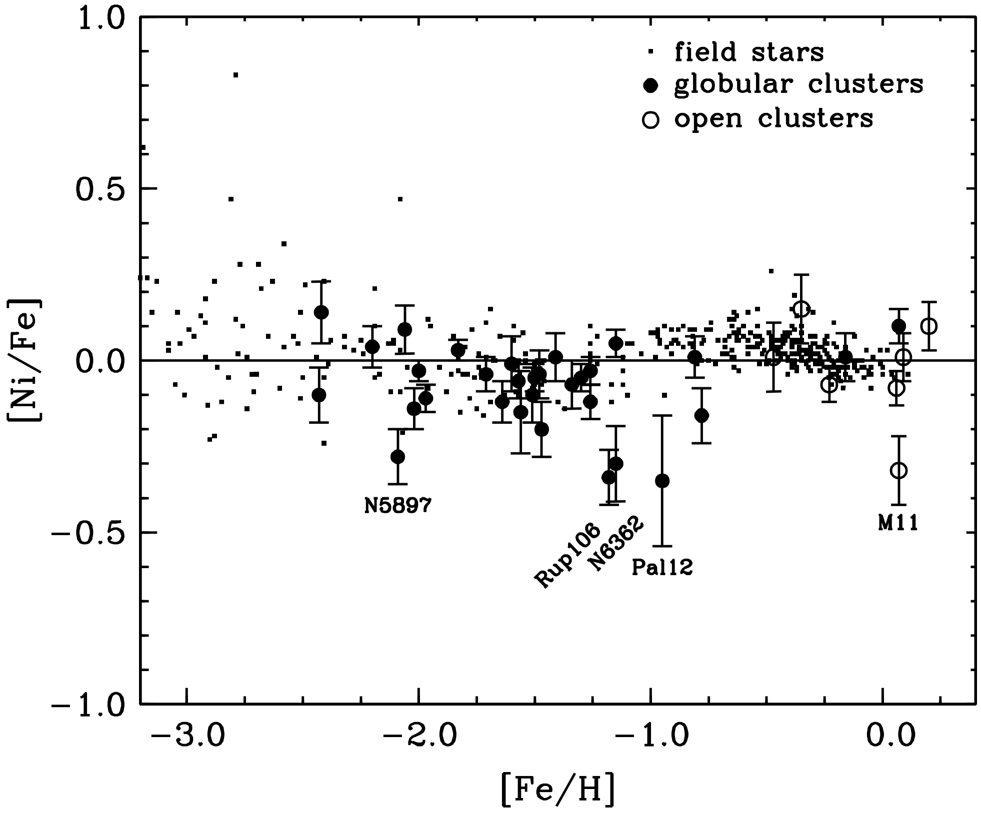

Fig. 1.1. Relative [Ni/Fe] abundance ratios as a function of stellar metallicity. The horizontal line at [Ni/Fe] = 0 indicates the solar [Ni/Fe] ratio. Labels of a few cluster names are placed to draw attention to clusters that deviate from the main trend. Very small filled squares represent field stars, filled circles are for globular clusters, and open circles are for open clusters. The error bars on the cluster points are sample standard deviations σ, and so represent the star-to-star abundance scatters within the clusters.

& Wallerstein (1997). Clearly this result warrants confirmation from future larger-sample studies. The [Ni/Fe] ratios of NGC 5897 and NGC 6362 are also based on just two stars per cluster, and come from the earliest survey chosen for inclusion here (Gratton 1987). The spectral resolving power of that study was only $R \equiv \lambda/\Delta\lambda \simeq$ 15,000. These clusters also should be prime candidates for further abundance studies. Finally, the open cluster M11 appears to have a significant Ni abundance deficiency (Gonzalez & Wallerstein 2000). This result cannot be blamed on sample size, for their survey included 10 cluster giants. Nor should data quality be an issue, as they obtained high signal-to-noise ratio data at $R \approx 40,000$. Gonzalez & Wallerstein briefly discuss possible explanations for this anomalous abundance ratio, invoking different mixtures of Type I and II supernovae (SNe) or unusual mass cuts in Type II SNe. But there are no definitive scenarios for the low [Ni/Fe] ratios in M11, and a comparative study of this cluster with other open clusters would be welcome.

In Figure 1.2 we compare Cu abundances in globular cluster and field stars. Since Cu

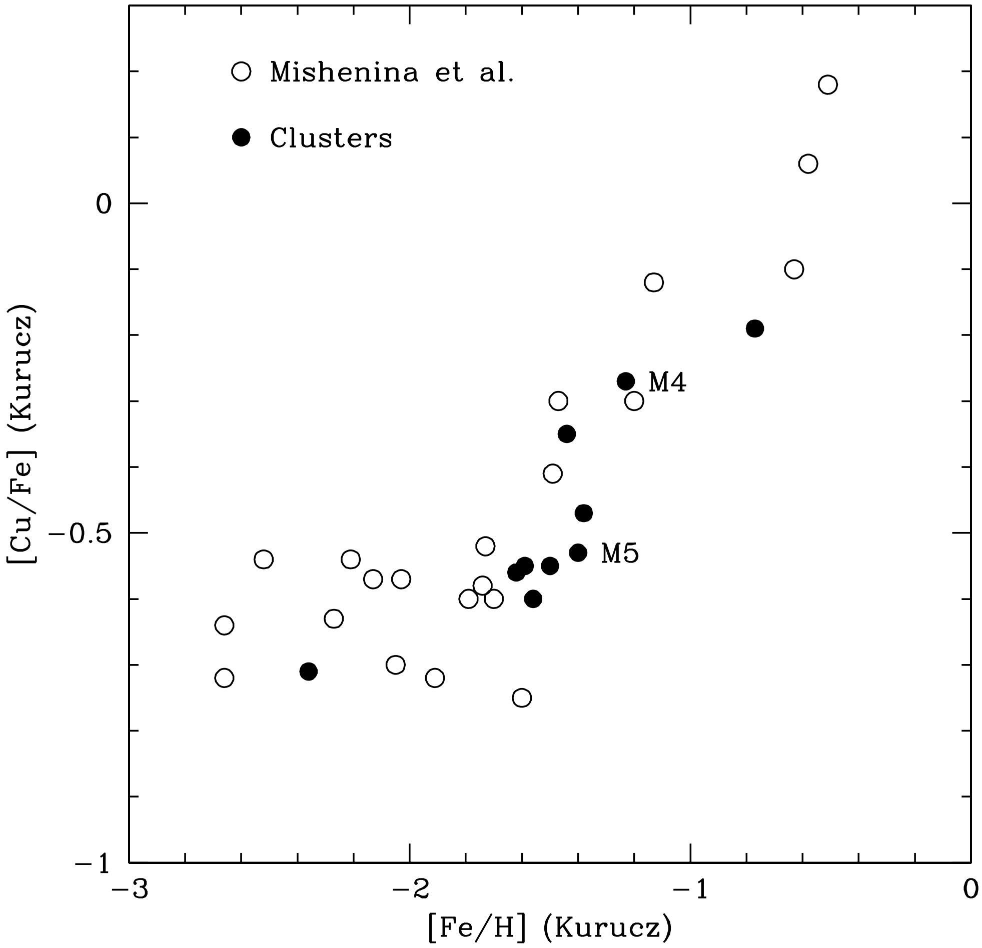

Fig. 1.2. Relative [Cu/Fe] abundance ratios as a function of stellar metallicity. The field star results (open circles) are those of Mishenina et al. (2002), while the globular cluster data are from Simmerer et al. (2003), who employed the spectroscopic data of earlier Lick-Texas group abundance studies in their derivation of Cu abundances.

abundance studies are not plentiful, this figure (taken from Simmerer et al. 2003) considers only their internally homogeneous large-sample globular cluster analysis and the new field-star survey of Mishenina et al. (2002). It has been known for some time that [Cu/Fe] declines steeply with decreasing [Fe/H] in halo field stars. Older studies (e.g., Sneden et al. 1991) suggested that the decline is a nearly linear function of decreasing metallicity, reaching [Cu/Fe] ≈ -1.0 at [Fe/H] ≈ -3.0. Misheninia et al. show that the relationship of [Cu/Fe] with metallicity may be more complex, with a rapid decline until [Fe/H] ≈ -1.7, then possibly reaching a near-constant [Cu/Fe] ≈ -0.6 at lower metallicities. But whatever the exact details of the Cu abundance trend, it is clear from Figure 1.2 that no obvious differences exist between the field stars and globular clusters.

The nucleosynthesis of Cu is not simple (see discussions in Cunha et al. 2002 and Mishenina et al. 2002), and no single explanation for the variation of [Cu/Fe] with [Fe/H] has proved to be adequate. Cu can be generated by slow neutron bombardment (the *s*-process), but a clear positive correlation of Cu with heavier *n*-capture elements has yet to be shown. Metallicity-dependent Cu yields in Type II SNe can roughly mimic the observed trends. On the other hand, if Type Ia SNe produce Cu more efficiently than do Type II SNe, the increasing influence of Type Ia's at higher metallicities can also reproduce the [Cu/Fe] trends. These nucleosynthesis scenarios must now deal with a further observational constraint: clusters and field stars obey the same relationship. Either major Fe-peak element nucleosynthesis occurs prior to formation of both clusters and field stars, or the generation of Cu is a process that is very finely tuned to the Fe metallicity.

1.4 Alpha Elements: Calcium

The α-elements are light even-Z elements in the range $6 \leq Z \leq 22$, whose dominant isotopes can be imagined as collections of α particles. Neglecting C and O, whose abundances are also alterable in proton-capture reactions, among the spectroscopically observable α-elements Ca is chosen here to represent the whole group. The reasons are the same as those for Ni: spectroscopic accessibility leading to plentiful abundance data in clusters and field stars alike. In Figure 1.3 we show [Ca/Fe] ratios for cluster and field stars. For field stars this figure illustrates the well-known rise in relative Ca abundances among disk stars as metallicity decreases from solar values down to [Fe/H] $\approx$ –1.0, retaining its elevated value of [Ca/Fe] $\approx$ +0.3 to +0.4 throughout the entire halo-star low-metallicity regime.

For the most part globular clusters mimic this trend in α-element enhancement, but a few exceptions can be spotted easily. As mentioned previously, the outer-halo, younger clusters Rup 106 and Pal 12 are relatively deficient in α-elements (Brown et al. 1997), and the underabundances of Ca exhibited in Figure 1.3 are well beyond observational/analytical uncertainties. Ca also appears to be deficient in 47 Tuc, but that result comes from a single study of just four stars (Brown & Wallerstein 1992), and clearly that cluster needs reinvestigation. The relatively high Ca abundance in the very metal-poor cluster NGC 4833 comes from only two stars observed by Gratton (1987) and should not at this time be viewed as discrepant (the reader is reminded that the small error bar is only an internal scatter measure).

Some relatively metal-rich clusters deserve comment here. NGC 6528 is a solar-metallicity globular ([Fe/H] = +0.07), and yet it exhibits the high [Ca/Fe] value of the metal-poor halo clusters (Carretta et al. 2001). Apparently Si abundances are also elevated in NGC 6528, which, when coupled with the apparent Mn deficiencies, argues that this very metal-rich cluster material bears the same Type II nucleosynthesis signature as is seen in the very metal-poor clusters. The situation is similar in NGC 6553, another relatively metal-rich cluster, where Barbuy et al. (1999) and Cohen et al. (1999) derive overabundances of both Ca and Si. The α-element abundances of these clusters provide reminders that Fe metallicity is a risky surrogate clock in describing the chemical enrichment of our Galaxy.

The [Ca/Fe] ratios of M71 stars are 0.1 to 0.2 dex larger than field stars of this [Fe/H] $\approx$ –0.8 metallicity regime (Ramírez & Cohen 2002). This result is based on a 25-star sample with representation from the cluster main sequence to the upper giant branch, and no variation in [Ca/Fe] is seen with evolutionary state. Moreover, a similar study of M5 by Ramírez & Cohen (2003) finds a mean value of [Ca/Fe] = +0.33, in excellent agreement with a mean [Ca/Fe] = +0.28 determined by Ivans et al. (2001) for 36 red giants in the same cluster. Small downward normalization shifts ($<$0.1 dex) could reduce the M71 [Ca/Fe] discrepancy with

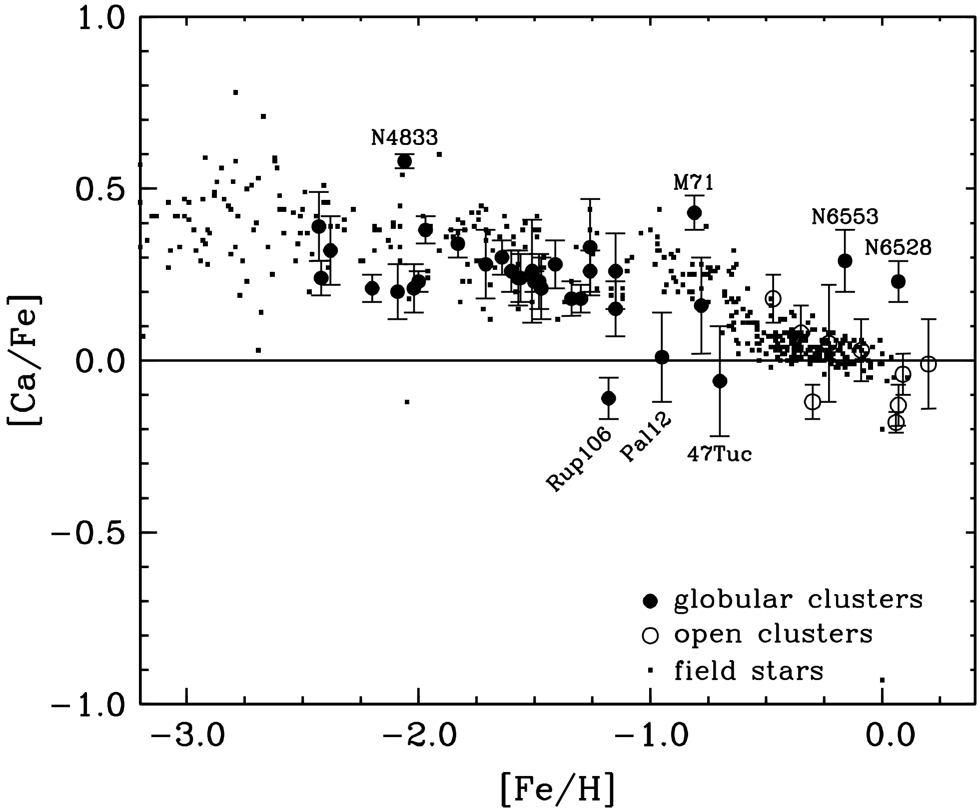

Fig. 1.3. Relative [Ca/Fe] abundance ratios as a function of stellar metallicity. The lines and symbols are as in Fig. 1.1.

field stars to the point where comment would be unwarranted, but for now we simply urge further [Ca/Fe] studies of metal-rich clusters to be undertaken.

Ratios of [Ca/Fe] may not give the entire story about the α-element abundances in globular clusters. Theoretical models of Type II SNe (e.g., Woosley & Weaver 1995) predict that the most massive Type II events heavily overproduce lighter α-elements like O and Mg, while the lower-mass events mainly produce the heavier α-elements Ca and Ti. Intracluster variations of O and Mg may mask any cluster-to-cluster variations in the ratios of these two elements with respect to Ca and Ti, but the [Si/Fe] and [Si/Ti] ratios do show some variations among both clusters and field stars of similar [Fe/H]. This is discussed in detail by Lee & Carney (2002) and Fulbright (2004). In brief, the variations in these ratios show matching correlations with respect to the kinematics (or at least the present galactocentric location) of the stars and clusters. Metal-poor stars and clusters closer to the Galactic Center show higher [Si/Fe] and [Si/Ti] ratios than similar-metallicity members of the outer halo.

1.5 Neutron-capture Elements: Europium, Barium, and Lanthanum

Europium (Z = 63) is the usual representative of the so-called *r*-process *n*-capture elements. These elements owe their production to rapid blasts of neutrons in some (as yet

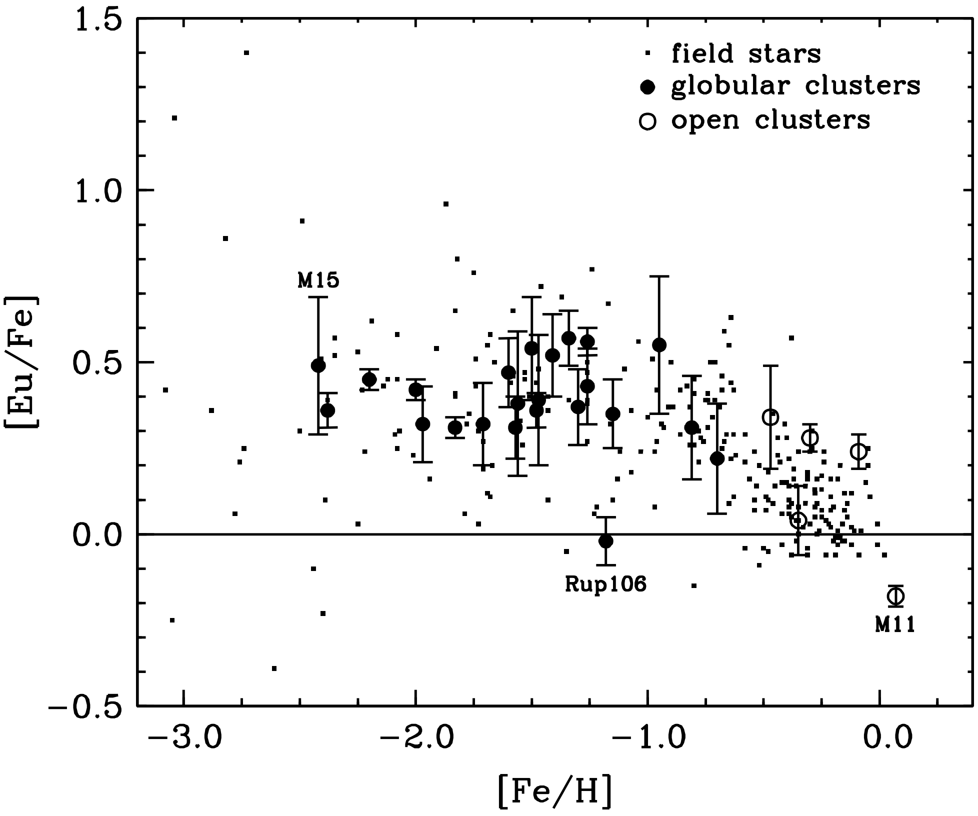

Fig. 1.4. Relative [Eu/Fe] abundance ratios as a function of stellar metallicity. The lines and symbols are as in Fig. 1.1.

ill defined) event(s) associated with the explosive deaths of massive stars. Most descriptions of the evolution of *r*-process elements in the Galaxy discuss Eu because useful transitions of Eu II occur in both blue and red spectral regions. No other *r*-process-dominated *n*-capture element (e.g., Gd, Dy, Ho) can be as easily observed in field and cluster stars.

In Figure 1.4 we correlate [Eu/Fe] ratios with [Fe/H] metallicities, and comparison of this figure with Figure 1.3 suggests that in field stars Eu abundances increase with decreasing metallicity in much the same fashion as do the α-elements, but with far more star-to-star scatter than is seen for Ca. The scatter itself increases with decreasing metallicity (see, e.g., Truran et al. 2002 and Cowan & Sneden 2004 for more extensive discussion and references to individual studies). But with the lone exception of Rup 106, mean [Eu/Fe] values in globular clusters exhibit little cluster-to-cluster variation, and the typical σ values of $\sim$0.15 dex show that Eu does not vary substantially within most clusters.

Rup 106 is an outlier in Figure 1.4 just as it was in Figures 1.1 and 1.3. However, Eu does not appear to be underabundant in Pal 12, the other outer-halo cluster studied by Brown et al. (1997). Although the Pal 12 [Eu/Fe] result is based just on one star, it is worth noting that Brown et al. derive higher abundances in Pal 12 than Rup 106 for all four *n*-capture elements (Zr, Ba, La, Eu) in common between the two clusters. The offset in Eu abundance

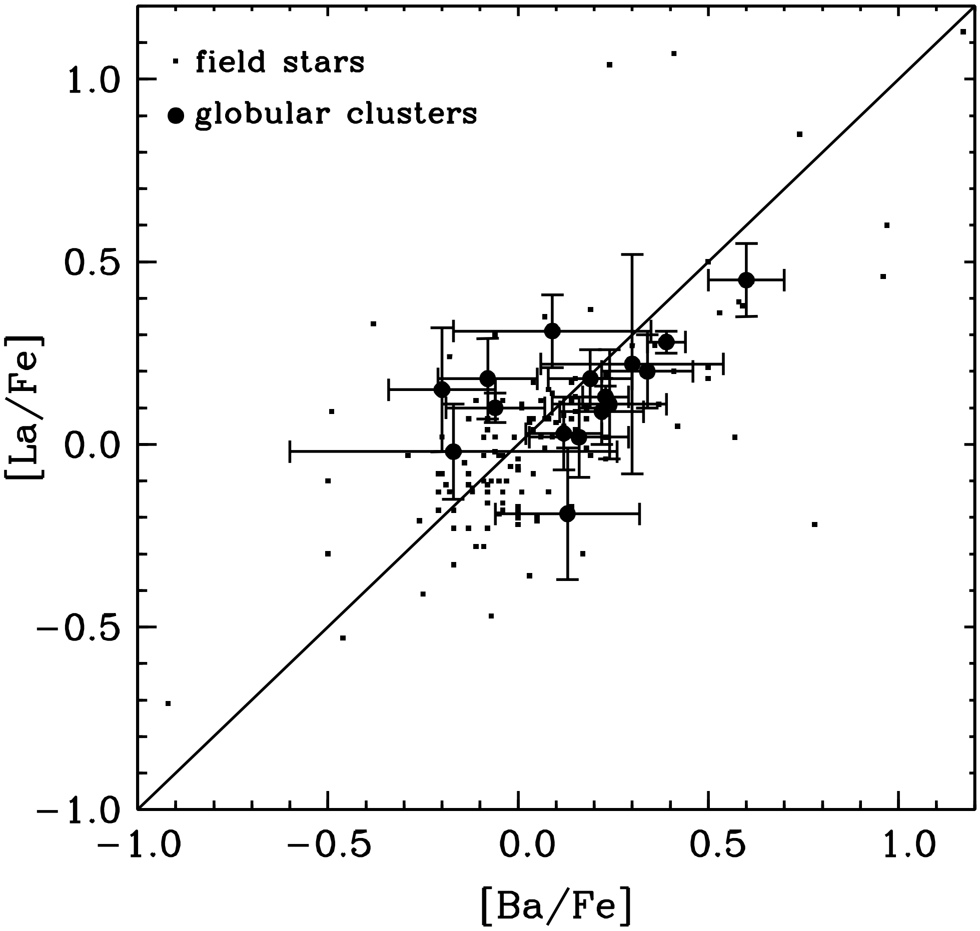

Fig. 1.5. [Ba/Fe] and [La/Fe] ratios in cluster and field stars. The symbols are as in Fig. 1.1; the diagonal line represents [Ba/Fe] = [La/Fe].

between Pal 12 and Rup 106 appears to be real. The most metal-poor cluster, M15, also deserves comment here. The mean [Eu/Fe] value shown in Figure 1.4 is from the relatively recent abundance study of 18 giant stars by Sneden et al. (1997). While the mean M15 [Eu/Fe] agrees well with other globular clusters, the star-to-star scatter (σ = 0.20) is larger than seen in most other clusters. The scatter is real, as can be seen in direct comparisons of spectra (Fig. 2 of Sneden et al.1997). M15 is the only globular cluster with confirmed general internal scatter in Eu abundances.

Ba and La in the solar system originated mostly in *s*-process *n*-capture synthesis; thus, their observed abundances should roughly rise and fall together. In Figure 1.5 we test this assertion by plotting these two abundances (when both are reported in the literature) for field and cluster stars. A correlation does exist, albeit with a discouraging amount of scatter. The analytical difficulties for Ba II and La II lines are different: Ba II lines are strong, often to the point of saturation, so that Ba abundances depend strongly on adopted microturbulent ve-

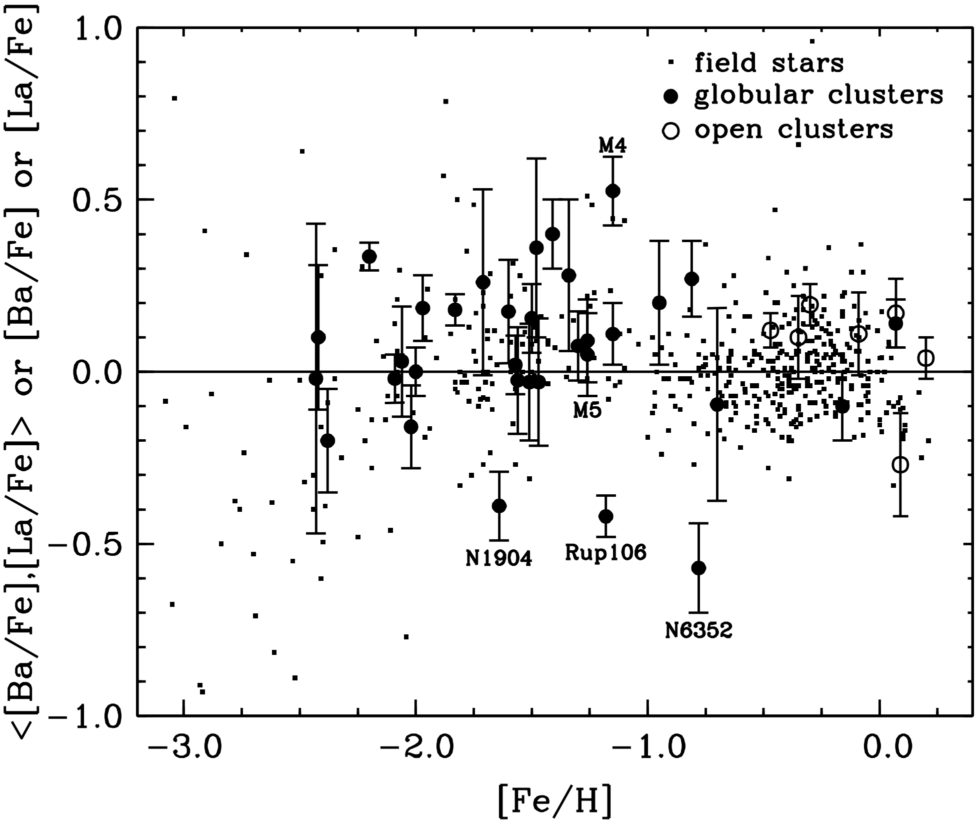

Fig. 1.6. Combined [Ba,La/Fe] ratios as a function of stellar metallicity. For stars with abundances reported for both elements, the ordinate is <[Ba/Fe],[La/Fe]>, and for stars with only Ba or La abundances, the ordinate is simply [Ba/Fe] or [La/Fe], as appropriate. The lines and symbols are as in Fig. 1.1.

locity values; La II lines are weak, often near the point of undetectability, so La abundances depend on obtaining very good signal-to-noise ratio spectra. The observed star-to-star scatters in Ba and La do not appear to be clearly correlated in most globular clusters, suggesting that observational errors dominate the variations within individual clusters.

Therefore, we have chosen to average [Ba/Fe] and [La/Fe] abundance ratios wherever possible in order to mute the observational scatter, and in Figure 1.6 we present these averaged abundance ratios as a function of stellar metallicity. For stars with only [Ba/Fe] or [La/Fe] values available, those have been plotted instead. In field stars, Ba and La abundances have very large (and real) scatter at lowest metallicities, just as Eu does (Fig. 1.4). But unlike Eu, there is little discernible change in the mean [Ba,La/Fe] level with decreasing metallicity. Plots of [Eu/Ba] or [La/Ba], not shown here, confirm that on average metal-poor globular cluster stars have excess Eu abundances, and hence greater *r*-process contributions to the *n*-capture elements than does solar system material.

Relative *r*-process dominance has been confirmed in detail for M15. Sneden et al. (1997) found that Ba abundances varied from star to star, but mostly in lock-step with Eu, main-

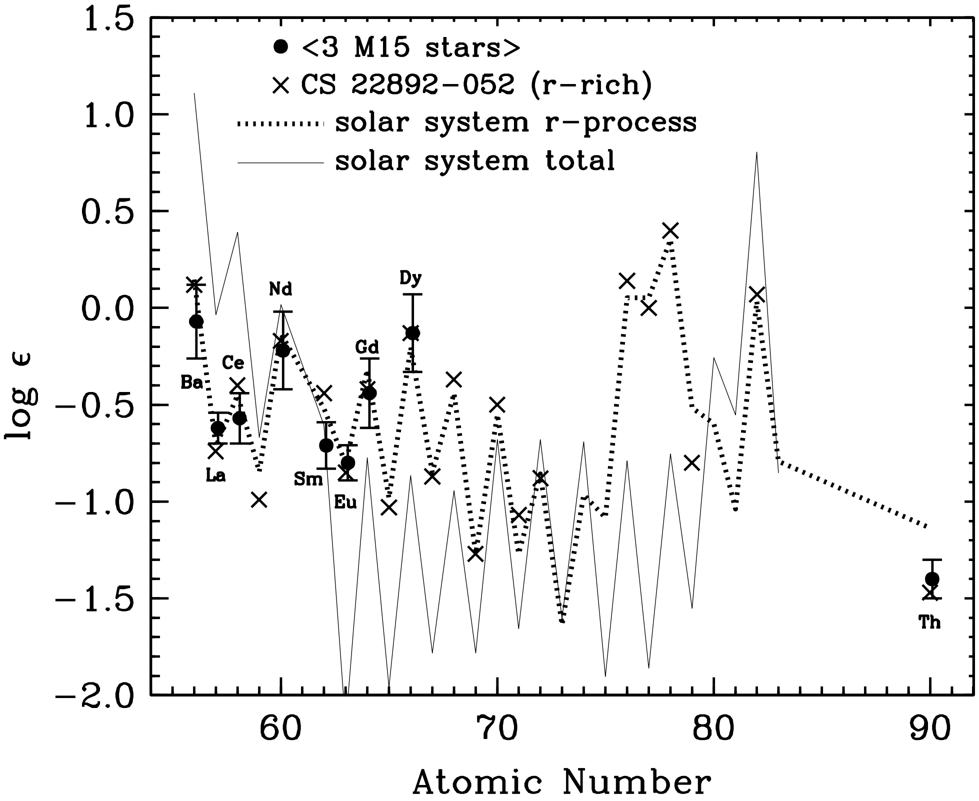

Fig. 1.7. Observed absolute abundances, $\log \epsilon(X) \equiv \log_{10}(N_X/N_H) + 12.0$ of heavy *n*-capture elements in the *r*-process-rich field giant CS 22892–052 (Sneden et al. 2003) and in M15 (the mean of three stars; Sneden et al. 2000b). Also shown are two scaled solar system abundance curves (Burris et al. 2000), one for the total elemental abundances and one for the amount of each element estimated to be due to *r*-process-only synthesis.

taining [Eu/Ba] ≈ +0.4 in all but one out of 18 stars of their sample. Most strong *n*-capture transitions in cool stars occur at $\lambda < 5000$ Å, and so Sneden et al. (2000b) reobserved three of these M15 giants in the blue spectral region. In Figure 1.7 we show a comparison of M15 *n*-capture abundances with those of the *r*-process-rich field giant CS 22892–052 and with two solar system abundance curves. These data clearly show that an *r*-process-dominated abundance pattern exists, confirming and strengthening the role of high-mass stellar explosive nucleosynthesis in the generation of M15's overall heavy element abundance pattern.

1.6 Proton-capture Elements: Oxygen, Sodium, and Aluminum

Nearly all globular clusters appear to possess star-to-star abundance variations in at least some of the light elements C, N, O, Na, Mg, and Al. These variations do not occur at random, as there are distinct correlations and anticorrelations among these element abundances. These relationships lead to an assertion that at some time(s), in some place(s) in globular cluster environments large amounts of stellar mass have been subjected to various proton-capture nuclear fusion cycles: C-N, O-N, Ne-Na, and Mg-Al.

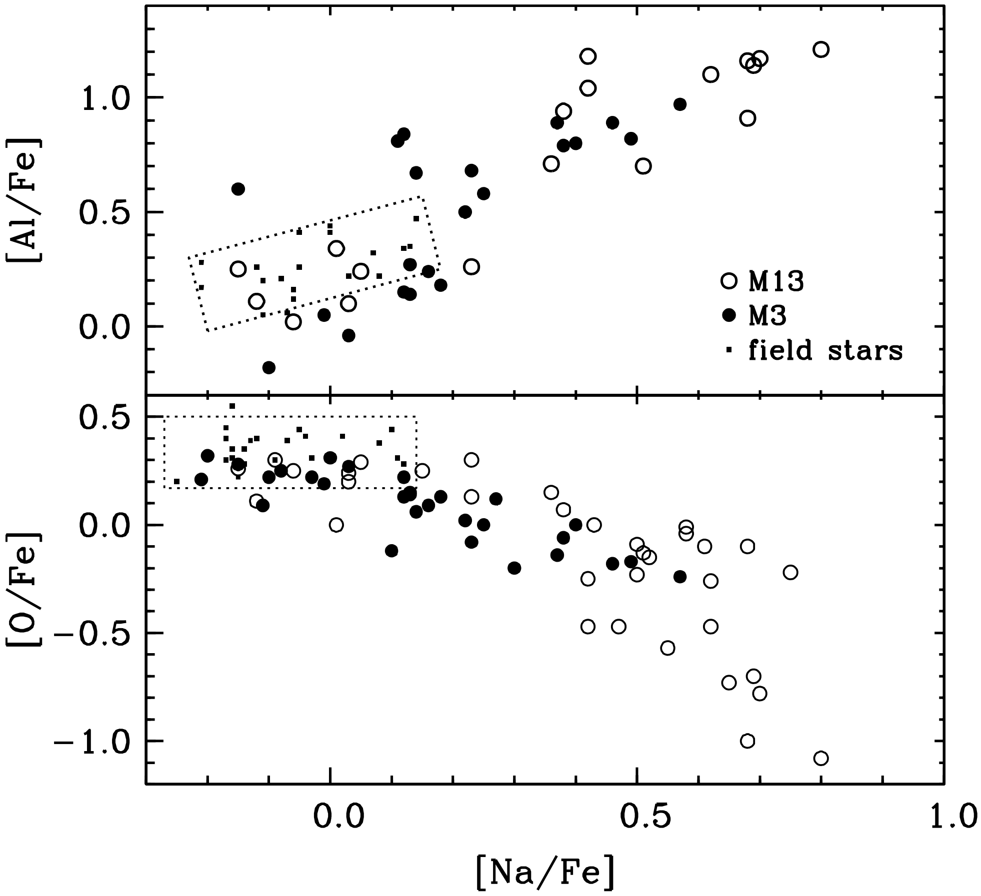

Fig. 1.8. Correlations of relative O and Al abundances with Na abundances in M3 and M13 (Sneden et al. 2004), and in field stars (Fulbright 2000 for the Na and Al data of the top panel; Gratton et al. 2000 for the O and Na data of the bottom panel). The data for O are only those derived from analyses of [O I] lines, which were also employed for the cluster abundances. Dashed-line boxes have been drawn in each panel to emphasize the locations of the field-star points.

Space available here does not permit a comprehensive discussion of the large observational literature on proton-capture element abundances in globular clusters; the reader is referred again to the reviews cited in §1.1. Here we simply note three observational facts that have led to ongoing debate on the origin of these cluster abundance variations. First, the existence of O-Na and Mg-Al anticorrelations (e.g., Fig. 9 of Kraft et al. 1997) leads to fusion-region temperature estimates of $\gtrsim 40\times10^6$ K. Such temperatures are not predicted to exist in the interiors of the low-mass red giants we now observe in globular clusters. Second, some proton-capture element abundance variations have been observed in stars at or near globular cluster main sequences (e.g., Briley & Cohen 2001). Third, some evidence exists for changes in some of these elemental abundances with luminosity in a few clusters (Kraft et al. 1997). These facts do not lead to simple conclusions that the light element abundance variations either were wholly created in the stars we see today, or are the products of a previous generation of intermediate-mass stars in the clusters.

Our discussion is limited to a reemphasis on the fundamental differences in proton-capture abundances between cluster and field stars. In Figure 1.8 we show the ranges of O, Na, and Al abundances in the well-studied cluster pair M3 and M13, and the corresponding much smaller ranges of these elements in the halo field. This figure is only one of many similar ones that could have been displayed, as many clusters have proton-capture abundance variations. To date, no confirmed case of a halo field star possessing "highly processed" light element abundances (e.g., large depletions of C, O, and possibly Mg, accompanied by large enhancements of N, Na, and Al) has been reported in the literature. Whatever the final outcome of the debate on the origin of these abundance effects in globular clusters, it will undoubtedly involve the higher stellar densities in the clusters that do not now exist in the general halo field (and, apparently, never did exist).

1.7 Summary and Conclusions

A review of representative heavy elements in globular clusters and in individual halo field stars has been conducted. We conclude that the nucleosynthesis events that created the Fe-peak elements and α-elements in these two populations were essentially the same. Some differences exist in detail among the *n*-capture elements, but *on average* little differences are found between field and cluster stars. The clearest distinction between these populations remains within the proton-capture element group.

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References

Barbuy, B., Renzini, A., Ortolani, S., Bica, E., & Guarnieri, M. D. 1999, A&A, 341, 539
Bragaglia, A., et al. 2001, AJ, 121, 327
Briley, M. M., & Cohen, J. G. 2001, AJ, 122, 242
Brown, J. A., & Wallerstein, G. 1992, AJ, 104, 1818
Brown, J. A., Wallerstein, G., Geisler, D., & Oke, J. B. 1996, AJ, 112, 1551
Brown, J. A., Wallerstein, G., & Gonzalez, G., 1999, AJ, 118, 1245
Brown, J. A., Wallerstein, G., & Zucker, D. 1997, AJ, 114, 180
Burris, D. L., Pilachowski, C. A., Armandroff, T. E., Sneden, C., Cowan, J. J., & Roe, H. 2000, ApJ, 544, 302
Carretta, E., Cohen, J. G., Gratton, R. G., & Behr, B. B. 2001, AJ, 122, 1469
Carretta, E., & Gratton, R. G. 1997, A&AS, 121, 95
Carretta, E., Gratton, R., Cohen, J. G., Beers, T. C., & Christlieb, N. 2002, AJ, 124, 481
Castilho, B. V., Pasquini, L., Allen, D. M., Barbuy, B., & Molaro, P. 2000, A&A, 361, 92
Christlieb, N., et al. 2002, Nature, 419, 904
Cohen, J. G. 1978, ApJ, 223, 487
——. 1979, ApJ, 231, 751
——. 1980, ApJ, 241, 981
——. 1981, ApJ, 247, 869
Cohen, J. G., Gratton, R. G., Behr, B. B., & Carretta, E. 1999, ApJ, 523, 739
Covey, K. R., Wallerstein, G., Gonzalez, G., & Vanture, A. D. 2003, PASP, 115, 819

Cowan, J. J., & Sneden, C. 2004, in Carnegie Observatories Astrophysics Series, Vol. 4: Origin and Evolution of the Elements, ed. A. McWilliam & M. Rauch (Cambridge: Cambridge Univ. Press), in press
Cunha, K., Smith, V. V., Suntzeff, N. B., Norris, J. E., Da Costa, G. S., & Plez, B. 2002, AJ, 124, 379
Edvardsson, B., Pettersson, B., Kharrazi, M., & Westerlund, B. 1995, A&A, 293, 75
Fulbright, J. P. 2000, AJ, 120, 1841
——. 2004, in Carnegie Observatories Astrophysics Series, Vol. 4: Origin and Evolution of the Elements, ed. A. McWilliam & M. Rauch (Pasadena: Carnegie Observatories, http://www.ociw.edu/ociw/symposia/series/symposium4/proceedings.html)
Gonzalez, G., & Wallerstein, G. 1998, AJ, 116, 765
——. 2000, PASP, 112, 1081
Gratton, R. G. 1987, A&A, 179, 181
Gratton, R. G., & Contarini, G. 1994, A&A, 283, 911
Gratton, R. G., & Ortolani, S. 1989, A&A, 211, 41
Gratton, R. G., & Sneden, C. 1991, A&A, 241, 501
Harris, W. E. 1996, AJ, 112, 1487 (http://physun.mcmaster.ca/ harris/mwgc.dat)
Helfer, H. L., Wallerstein, G., & Greenstein, J. L. 1959, ApJ, 129, 700
Ivans, I. I., Kraft, R. P., Sneden, C., Smith, G. H., Rich, R. M., & Shetrone, M. 2001, AJ, 122, 1438
Ivans, I. I., Sneden, C., Kraft, R. P., Suntzeff, N. B., Smith, V. V., Langer, G. E., & Fulbright, J. P. 1999, AJ, 118, 1273
Johnson, J. A. 2002, ApJS, 139, 219
Johnson, J. A., & Bolte, M. 2001, ApJ, 544, 888
King, J. R., Soderblom, D. R., Fischer, D., & Jones, B. F. 2000, ApJ, 533, 944
Kraft, R. P. 1994, PASP, 106, 553
Kraft, R. P., & Ivans, I. I. 2003, PASP, 115, 143
——. 2004, Carnegie Observatories Astrophysics Series, Vol. 4: Origin and Evolution of the Elements, ed. A. McWilliam & M. Rauch (Pasadena: Carnegie Observatories, http://www.ociw.edu/ociw/symposia/series/symposium4/proceedings.html)
Kraft, R. P. Sneden, C., Langer, G. E., Shetrone, M. D., & Bolte, M. 1995, AJ, 109, 2586
Kraft, R. P., Sneden, C., Smith, G. H., Shetrone, M. D., & Fulbright, J. P. 1998, AJ, 115, 1500
Kraft, R. P., Sneden, C., Smith, G. H., Shetrone, M. D., Langer, G. E., & Pilachowski, C. A. 1997, AJ, 113, 279
Lee, J.-W., & Carney, B. W. 2002, 124, 1511
McWilliam, A., Geisler, D., & Rich, R. M. 1992, PASP, 104, 1193
McWilliam, A., Preston, G. W., Sneden, C., & Searle, L. 1995, AJ, 109, 2757
Mishenina, T. V., Kovtyukh, V. V., Soubiran, C., Travaglio, C., & Busso, M. 2002, A&A, 396, 189
Peterson, R. C. 1980, ApJ, 237, L87
Pilachowski, C. A. 1984, ApJ, 281, 614
Ramírez, S. V., & Cohen, J. G. 2002, AJ, 123, 3277
——. 2003, AJ, 125, 224
Reddy, B. E., Tomkin, J., Lambert, D. L., & Allende Prieto, C. 2003 MNRAS, 340, 304
Ryan, S. G., Norris, J. E., & Beers, T. C. 1996, ApJ, 471, 254
Shetrone, M. D. 1996, AJ, 112, 1517
Shetrone, M. D., & Keane, M. J. 2000, AJ, 119, 840
Simmerer, J., Sneden, C., Ivans, I. I., Kraft, R. P., Shetrone, M. D., & Smith, V. V. 2003, AJ, 125, 2018
Simmerer, J. A., Sneden, C., Woolf, V. M., & Lambert, D. L 2001, BAAS, 199, 9110
Smith, G. H., Sneden, C., & Kraft, R. P. 2002, AJ, 123, 1502
Sneden, C. 2000, in 35th Liège Int. Ap. Coll.: The Galactic Halo, from Globular Clusters to Field Stars, ed. A. Noels et al. (Liège Belgium: Institut d'Astrophysique et de Géophysique), 159
Sneden, C., et al. 2003, ApJ, 591, 936
Sneden, C., Gratton, R. G., & Crocker, D. A. 1991, A&A, 246, 354
Sneden, C., Johnson, J., Kraft, R. P., Smith, G. H., Cowan, J. J., & Bolte, M. S. 2000b, ApJ, 536, 85
Sneden, C., Kraft, R. P., Guhathakurta, R., Peterson, R. C., & Fulbright, J. P., 2004, AJ, submitted
Sneden, C., Kraft, R. P., Shetrone, M. D., Smith, G. H., Langer, G. E., & Prosser, C. F. 1997, AJ, 114, 1964
Sneden, C., Pilachowski, C. A., & Kraft, R. P. 2000a, AJ, 120, 1351
Spite, M. 2004, Carnegie Observatories Astrophysics Series, Vol. 4: Origin and Evolution of the Elements, ed. A. McWilliam & M. Rauch (Pasadena: Carnegie Observatories, http://www.ociw.edu/ociw/symposia/series/symposium4/proceedings.html)
Truran, J. W., Cowan, J. J., Pilachowski, C. A., & Sneden, C. 2002, PASP, 114, 1293

Woolf, V. M., Tomkin, J., & Lambert, D. L. 1995, ApJ, 453, 660
Woosley, S. E., & Weaver, T. A. 1995, ApJ, 448, 315
Yong, D., et al. 2003, private communication
Zinn, R., & West, M. J. 1984, ApJS, 55, 45