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Abundance Trends of Alpha and Fe-Peak Elements in Globular Clusters

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Abstract. A fairly large fraction of Galactic globular clusters have been subjected to some sort of high spectral resolution abundance analysis in the past two decades. Several clusters have enjoyed the scrutiny of large numbers (>20) of their giant stars at very high resolution (R > 40,000) and signal-to-noise (>100), and such investigations have even begun to probe the fainter subgiant cluster members. Other clusters have seemed to be of lesser interest, having only studies of a few of their brighter members reported in the literature. This brief overview will consider the abundance trends of some key element groups, including the alpha, Fe-peak, neutron-capture, and proton-capture elements. Some comparison with field stars will be attempted to illustrate where stellar population differences between clusters and the field seem to occur. Suggestions for renewed observational attention will be drawn to specific clusters whose chemical origin appears to be substantially different than the general Galactic halo.

Key words. Globular clusters – Galactic halo – Chemical compositions

1. Introduction

Much of the current interest in globular cluster chemical compositions centers on attempts to derive accurate metallicity scales for them, and to understand their very substantial intra- and inter-cluster abundance variations of the lighter elements, A < A(Si). In the discussion of globular cluster chemistry to be given here we will ignore both of these important issues, but for different reasons.

Metallicities, which usually are equated with mean [Fe/H] values derived from individual, are fundamental inputs to globular cluster isochrones. They feed directly into cluster age determinations and distance scale computations, and are typically determinable at present to the 0.2 dex level. Several large efforts have systematically investigated cluster metallicities, including those of Zinn & West (1984), Rutledge, Hesser, & Stetson (1997), and Carretta & Gratton (1997). But, as Kraft & Ivans (2003) state in the latest attempt to define an overall cluster metallicity scale, "The conclusion we reach is that there exists no definitive set of cluster metallicities that are systematically reliable on the 0.02–0.05 dex level. Any discussion using cluster abundances needs to state clearly the underlying assumptions concerning models used ... what is meant by 'metallicity', which $T_{\rm eff}$ scale has been adopted, etc. If systematic effects on

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the 0.25 dex level are irrelevant to the discussion, then almost anybody's metallicity scale is acceptable." Significant tightening of metallicity uncertainties probably will require progress on multiple fronts: accurate transition probabilities for more Fe I and Fe II lines, further investigation of possible departures from local thermodynamic equilibrium in metal-poor stellar atmospheres, etc.

Light elements that are susceptible to abundance changes from proton-capture reactions, such as the pp, CN, ON, NeNa, and MgAl cycles, exhibit star-to-star abundance variations in globular clusters far in excess of the modest variations seen in halo field stars. These abundance variations are seen in varying degrees in Li, C, N, O, Na, Mg, and Al, and the effects are more pronounced in some clusters than in others. This subject has a large literature and deserves a longer discussion than is possible here. For some general reviews see, e.g., Smith (1987), Kraft (1994), and Sneden (1999,2000). Report of a new study of light elements in the well-studied clusters M3 and M13 is given in this volume by Kraft (2004).

In this paper we review a few globular cluster abundance ratio trends with overall metallicity for the heavier elements, those with A ≥ A(Si). The general outline follows more detailed discussions by Sneden, Ivans, & Fulbright (2003) and Gratton, Sneden, & Carretta (2004). The reader is referred to those papers for a complete list of clusters included in our discussion (32 globular clusters, 8 open clusters), information of the number of stars in each cluster that contribute to the cluster means, and literature references for the individual abundance studies. The globular cluster abundance trends will be compared to those of halo field stars and selected open clusters.

2. Fe-Peak Elements

The Fe-peak elements are those in the range $21 \leq Z \leq 30$, exclusive of Ti which is (also) the heaviest of the α-elements. Of the Fe-peak elements other than Fe itself, Ni has been studied most extensively in globular clusters due, (a) to existence of a number of accessible Ni I lines in the yellow-red spectral region, and (b) to the relative insensitivity of [Ni/Fe] abundance ratios on stellar atmospheric parameter uncertainties.

In Figure 1 we display globular cluster, open cluster, and field star [Ni/Fe] values as a function of [Fe/H] metallicities. The cluster points are simple means of the abundances of individual stars within each cluster, and the error bars represent the sample standard deviations σ of these means. Abundances of Ni have been reported for many more field stars than cluster stars, so in this figure the field star trend is represented by average lines. To form these average values, we employed the field-star results of McWilliam et al. (1995), Ryan et al. (1996), Feltzing & Gustafsson (1998), Fulbright (2000), Johnson & Bolte (2001), Gratton et al. (2003), Reddy et al. (2003), and Spite et al. (2003). Mean [Ni/Fe] abundances were formed with these data in 0.2 dex intervals of [Fe/H], and the solid line in Figure 1 represents that average field-star trend. The dashed lines above and below the solid line represents the scatter in [Ni/Fe] at a given [Fe/H], as indicated by the σ values of the means.

Considering first the field stars, it is clear from Figure 1 that [Ni/Fe] $\simeq$ 0.0 at all metallicities. The star-to-star scatter increases as [Fe/H] decreases, but this probably is a result of decreasing accuracy of individual abundance determinations (decreasing metallicity roughly goes with decreasing apparent brightness; very metal-poor stars are faint, and spectra obtained for such stars are often of lower resolution and S/N than those obtained for the brighter metal-rich stars). But over more than three decades of metallicity there is no evidence for deviation of Ni-to-Fe ratios from the solar system value.

Generally both globular and open cluster [Ni/Fe] abundance ratios displayed in Figure 1 agree with their field-star counterparts, indicating (probably unsurprisingly) that nucleosynthesis of Ni and Fe proceeded in similar ways in the stars that seeded the cluster and field ISMs. Of course, there are no globular clusters with [Fe/H] < –2.5, so the very low-metallicity domain is unsampled by

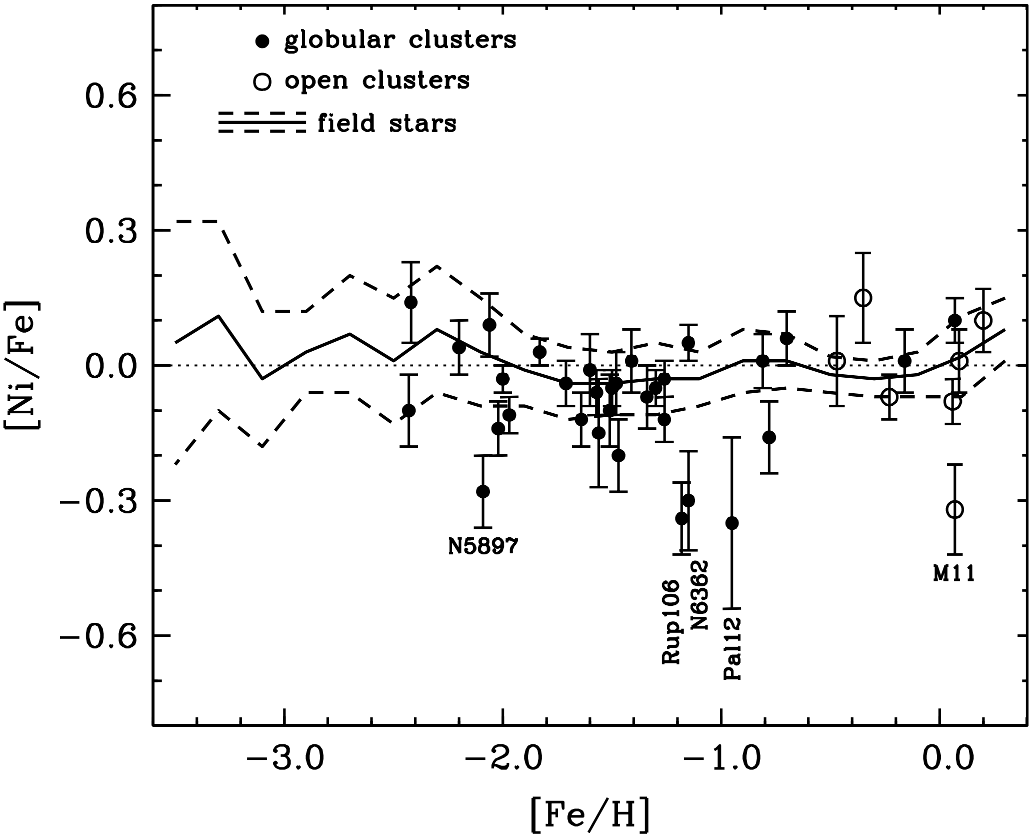

Fig. 1. Correlation of [Ni/Fe] with [Fe/H] metallicity in field and cluster stars. Each globular and open cluster point is the mean value for a single cluster. The lines representing the field-star trend with metallicity are averages of abundances in 0.2 dex metallicity bins, as described in the text. The solid line is shows the mean trend, and the dashed lines indicate the scatter about the mean. The dotted line is drawn at [Ni/Fe] =0.0.

these objects. A handful of clusters appear to have discordantly low values of [Ni/Fe]. These are discussed in Gratton et al. (2004). Briefly, the NGC 5897 and NGC 6362 points are from a relatively old study (Gratton 1987), and their entire abundance sets should be reinvestigated. The main current puzzle are the apparent low Ni abundances of two outer-halo clusters, Rup 106 and Pal 12 (Brown, Wallerstein, & Zucker 1997). The abundance anomalies of these clusters extend especially to the α-elements, which will be discussed in the next section. Finally, the open cluster M11 (Gonzalez & Wallerstein 2000) also exhibits low anomalously low [Ni/Fe], and this lacks a convincing nucleosynthetic explanation as of now.

Among the Fe-peak elements, only Mn and Cu show significant deviations from solar ratios in low-metallicity regimes: both of these elements are relatively underabundant. In Figure 2 we reproduce a comparison of field and globular cluster Cu abundances. This is a more restricted comparison than the one shown for Ni, as single abundance sources have been used: Mishenina et al. (2002) for the field stars, and Simmerer et al. (2003) for the globular cluster stars. Thus the uncertainties in comparing results from different investigations are reduced just to these two stud-

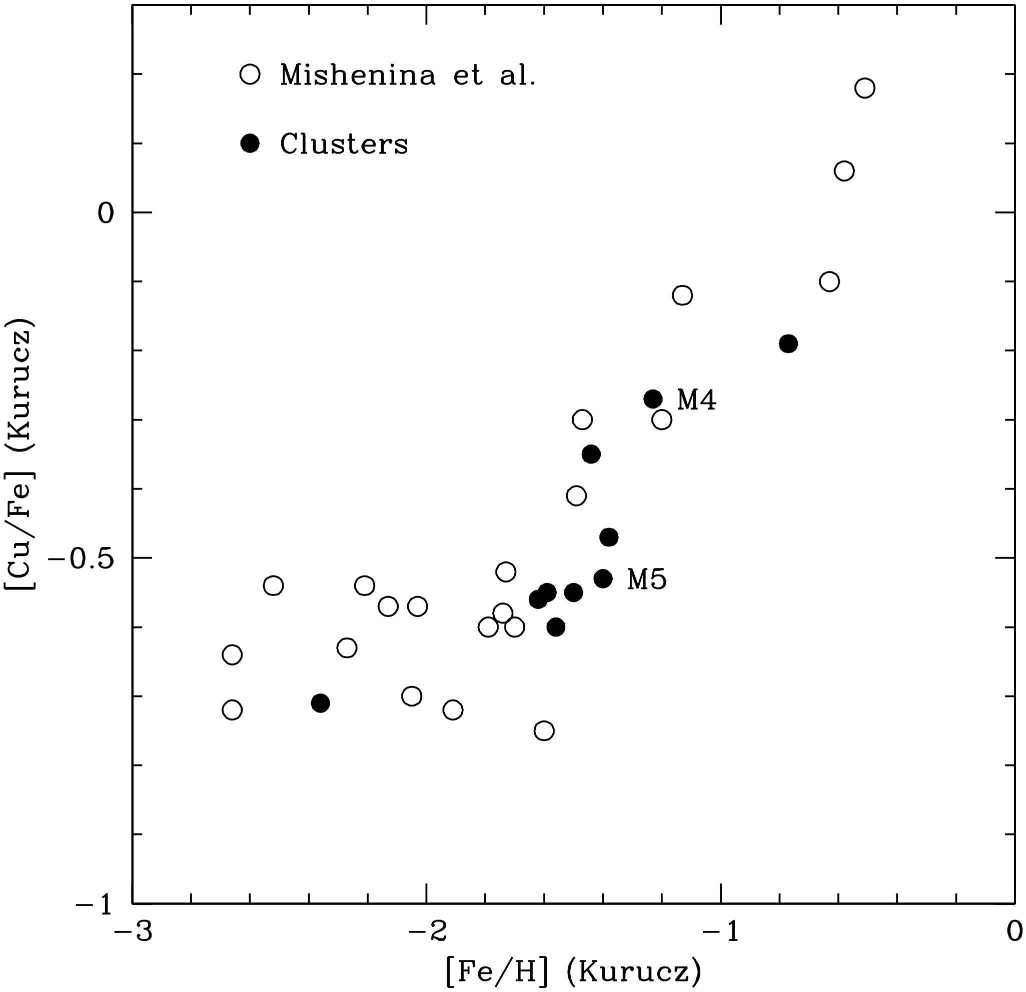

Fig. 2. Correlation of [Cu/Fe] with [Fe/H] metallicity in field and cluster stars, taken from Simmerer et al. (2003). The field star abundances (open circles) are from Mishenina et al. (2002), and the globular cluster abundances are from Simmerer et al.

ies, and see Simmerer et al. for a discussion of the [Cu/Fe] and [Fe/H] scale comparisons. The simple message to be taken from Figure 2 is that whatever the nucleosynthesis mechanism(s) happen to be responsible for the creation of Cu in high-mass stars and its return to the ISM, they are the same in the general halo field and in globular clusters. Therefore it seems clear that either Cu production is a finely-tuned function of initial stellar metallicity in the progenitor stars, or the seeding of globular clusters with Cu occurred prior to the isolation of individual clusters, in much larger-mass Galactic halo clouds. Some scattered results for Mn also indicate general agreement of halo field and cluster [Mn/Fe] ratios as a function of [Fe/H] metallicity (see Gratton et al. 2004 for further discussion), but much more observational work needs to be accomplished to solidify this conclusion.

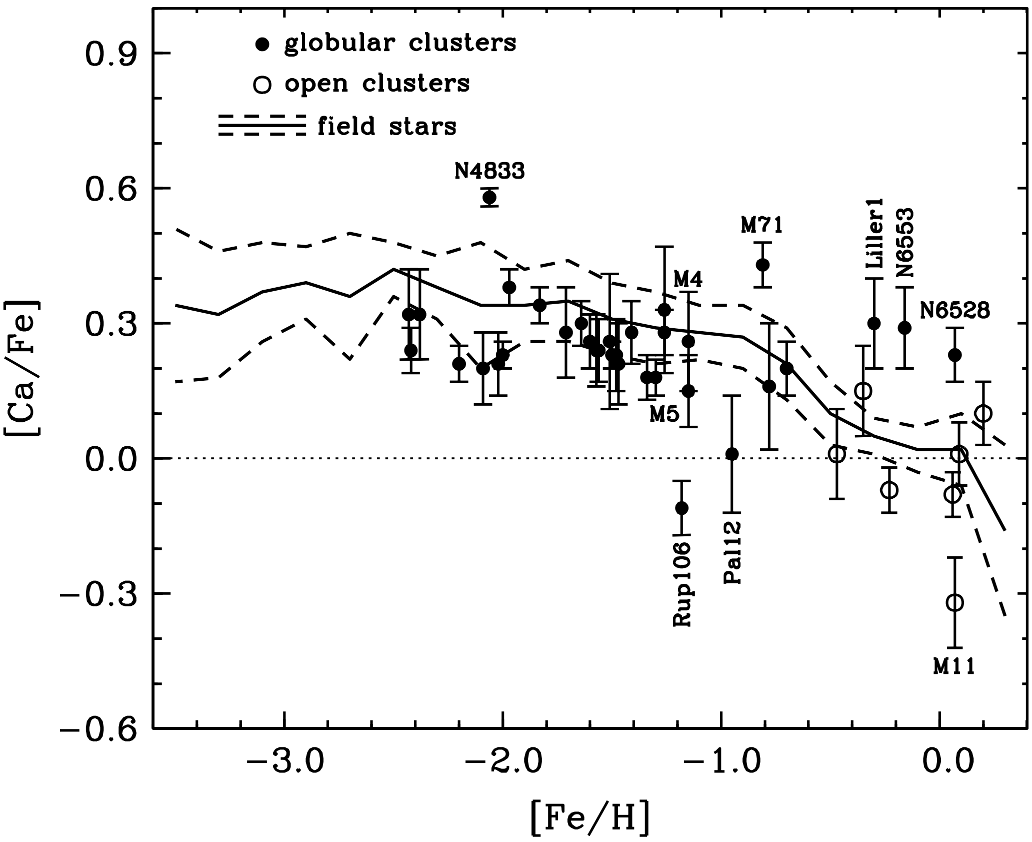

Fig. 3. Correlation with [Ca/Fe] abundance ratios with [Fe/H] metallicities. The lines and symbols are as in Figure 1.

3. Alpha Elements

The even-Z light elements are usually called α elements because their dominant isotopes are even multiples of He nuclei. For nearly 40 years they have known to be overabundant in halo field stars One would like to perform a comprehensive comparison of α elements in field and globular cluster stars, but this is not a trivial exercise. The problem lies with the general spectroscopic inaccessibility of several of these elements (Ne, Ar, S) at low metallicity, the participation of others (C, O, Mg) in proton-capture fusion cycles, and the membership of one (Ti) in both α and Fe-peak element groups. Unfortunately this leaves only Si and Ca as easily observed "pure" α elements.

The most reliable spectroscopic results over a wide metallicity range can be had for Ca, so in Figure 3 we show the same type of correlation for [Ca/Fe] with metallicity that was done for Ni in Figure 1. The reader can easily see that there are few surprises: both halo and globular cluster stars show Ca overabundances of 0.2–0.4 dex in the regions of [Fe/H] overlap, and the higher-metallicity open clusters have [Ca/Fe] ≃ 0.0, in accord with field disk stars. The probable explanation of the rise in Ca and other α-element abundance ratios with respect to Fe has been at hand for some time: high-mass stars that end their lives as Type II SNe are relatively efficient producers of α elements. These high mass stars would have been the first heavy element contributors to the halo field ISM, which consequently would have had large [α/Fe] ratios that are seen in the "second-generation" halo stars that are observed today.

The exceptions to the Ca overabundance trend at low metallicity may be more interesting than they were in the case of Ni. Ignoring the point of NGC 4833 from a relatively old study involving just two stars (Gratton & Ortolani 1989), the points for Rup 106 and Pal 12 (Brown et al. 1997) stand out. These clusters have large Galactocentric distances and may be several Gyr younger than the general globular cluster population, thus perhaps have been late additions to our Galaxy from a close encounter with one of its neighboring galaxies. Without a clear way to resolve this question, it may be better to concentrate on basic nucleosynthesis considerations: the progenitor stars to the ones observed in these two clusters probably included a larger Type I to Type II SN mix than is usually supposed to have occurred in the Galactic halo ISM. The IMFs may have been relatively deficient in high-mass stars, or star formation occurred more slowly, allowing lower-mass Type I events to contribute to the element mix. Attention in Figure 3 is also drawn to the existence of 2–3 metal-rich globular clusters with [Ca/Fe] $\sim +0.3$, much higher than those of their open cluster and field star counterparts at similar metallicities. Halo-star α-element abundances near solar metallicities provide an additional cautionary note about the inadvisability of using [Fe/H] as a surrogate for time in the Galaxy.

Finally, Si is overabundant in globular cluster and field stars, as expected for an α element, but Lee & Carney (2002), Fulbright (2000), and Stephens & Boesgaard (2002) find correlations with Galactocentric distance R: [Si/Fe] values increase with decreasing R. See Gratton et al. (2004) for further discussion of this trend. Here we simply comment that correlations of globular cluster [Ca/Fe] ratios reveal little if any variation with R. If Si production is a more sensitive function of stellar mass than is Ca production (e.g. see the discussion and references in McWilliam 1997), these differing trends may suggest that the IMF varied with position in the young Galaxy.

4. Neutron-Capture Elements

Neutron-capture elements include all those with $Z > 30$, because their dominant isotopes are created in slow and rapid neutron-capture reactions (the so-called *s*-process and *r*-process, respectively). The *r*-process probably can only occur in the death throes of high-mass stars, while the *s*-process is a by-product of He-burning in low-intermediate-mass stars. Globular cluster spectra are most often obtained in the yellow-red spectral regions where cool stars emit most of their flux, but most strong neutron-capture-species transitions occur in the blue-violet. Therefore abundances of only a handful of neutron-capture elements are normally reported in the cluster literature. Chief among these are Ba and La (prime representatives of the *s*-process), and Eu (the main representative of the *r*-process). In Sneden et al. (2003) and Gratton et al. (2004) various correlations of relative Ba, La, and Eu abundances as functions of metallicity are shown. Here we simple summarize the main conclusions of these reviews.

- Eu: this element is usually overabundant ([Eu/Fe] $\sim +0.4$) at all metallicities [Fe/H] ≤ -1.0. Whereas the star-to-star scatter in [Eu/Fe] increases toward lower metallicities, there is little evidence of this effect in globular clusters. Only one cluster defies this trend, the outer-halo member Rup 106, but curiously its "companion" cluster Pal 12 has normal (that is, overabundant) Eu. Large Eu production is consistent with substantial high-mass Type II SNe contributions to both the halo field and globular cluster ISMs. Only one globular cluster (M15, Sneden et al. 1997) has been proven to have an internal star-to-star variation in Eu (as well as in Ba).
- Ba, La: very approximately, [Ba/Fe] $\sim$ [La/Fe] ~ 0.0 But the cluster-to-cluster scatter at a given [Fe/H] ranges over more than 0.5 dex in these elements, and can be shown to be real, not observationally-induced. This may suggest that while the Eu abundances of globular clusters were implanted in the cluster ISMs as they were forming, the Ba, La abundances seen today

may have had substantial contributions from an early generation of intermediate-mass stars contained within the clusters themselves.

- Other neutron-capture elements: aside from a handful of transitions of Y II, Zr II, and Nd II, nearly all of the neutron-capture elements are spectroscopically accessible only in the blue-violet spectral regions. Further progress on describing the abundance evolution of these elements in globular clusters awaits systematic gathering of data in this wavelength domain of at least a few stars in many clusters.

5. Conclusions

This brief discussion of globular cluster abundances has emphasized those elements that are unaffected by the proton-capture synthesis reactions that have created large star-to-star and cluster-to-cluster light element variations. Comparisons of Ni, Cu, Ca, Ba, La, and Eu abundances in globular clusters and halo field stars reveals remarkable consistency for the most part, with very few intriguing exceptions that deserve further investigation. In generating the heavier elements, the stellar nucleosynthesis and expulsion of material into the ISM appears to have proceeded in nearly identical fashions in both of these low-metallicity Galactic sub-populations.

Further desirable abundance comparisons between clusters and field stars should include the determination of reliable Mn, Zn, and more representatives of the neutron-capture elements in a large number of clusters. But beyond improving the data on less-studied individual elements, a systematic study of certain key elements (e.g., Ca) in metal-rich globular clusters, open clusters, and the disk field should clear up the question of just what Galactic population the high metallicity end of the globular cluster distribution belongs to.

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