Session V

The Globular Cluster - Field Relation

Luca Pasquini enjoying *romantic lithium* in Globular Clusters.

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Globular cluster and halo field abundances: similarities and a few differences

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Abstract. The abundance distributions of cluster and field halo populations will be considered. Abundance data for most elements of the Periodic Table are much sparser for globular clusters than for individual halo field stars, mainly due to the relative lack of high resolution spectra in the blue for the former group. But the available data do suggest that, in spite of remaining uncertainties in the observational data, that chemical composition differences in the heavier elements (Fe-peak and beyond) are small, indicating common nucleosynthetic origins for all halo populations.

Keywords. Stars: abundances, stars: Population II, globular clusters: general

1. Introduction

Globular Clusters are large, self-contained stellar systems that were mostly formed near the beginning of our Galaxy. For the most part they appear to be mono-metallic in their Fe-group elements, ones that define our best-available estimates of "metallicity".† The ability to use photometry alone to deduce stellar parameters of temperature, surface gravity, and [Fe/H] has made globular clusters attractive objects for studies of Galactic chemical evolution. The relative faintness of even the giant stars in the closest clusters (typically $V < 11$) was a formidable barrier to large-scale chemical composition studies prior to the development of echelle spectrographs with CCD detectors attached to 4m and larger telescopes. Nonetheless, some pioneering studies were able to map out the general abundance ratios of a small number of accessible cluster members, beginning with the Helfer, Wallerstein, & Greenstein (1959) analysis of their photographic coudé spectrum of a single star in M13 ([Fe/H] $\sim$−1.5) and one in M92 ([Fe/H] $\sim$−2.3). The next clear milestones came with the first echelle spectrographs equipped with image tube/photographic detectors, leading to more systematic studies of bright giants of multiple clusters, e.g., Cohen (1983), Pilachowski (1984), references therein. The advent of CCD detectors fueled the next quantum leap in globular cluster spectroscopic studies, e.g., Dodorico *et al.* (1985), Spite *et al.* (1986), Spite *et al.* (1987). Since that time, thanks to ever-increasing overall spectrograph quantum efficiency, the jump to 8m-class telescopes, and increasing use of multiple-object spectrometers, many globular clusters have been subjected to large-sample chemical composition analysis, and many fundamental aspects of their abundances are now well established.

There have been several reviews of globular cluster chemical compositions, e.g., Smith (1987), Kraft (1994), Sneden (1999), Sneden (2000), Sneden, Ivans, & Fulbright (2004), and Gratton, Sneden, & Carretta (2004). Much of the research reported in these reviews, and in many papers by various teams reported in the present volume, concerns the light "proton-capture" elements, which are defined here as those whose abundant isotopes can

† We will not consider here the complex metallicity distribution of the massive globular cluster ω Cen. For a recent summary of research on that cluster see, e.g, Smith (2004).

be substantially altered in fusion cycles operating in hydrogen-rich stellar fusion zones at temperatures between 10^7 and 10^8 K. Many of the various observed correlations and anti-correlations in elemental abundances of C, N, O, Na, Mg, and Al clearly point to proton-fusion synthesis in hotter environments than appear to be possible in the interiors of main sequence, subgiant, and red giant low mass cluster stars. The origin of these abundance variations is not clear as yet, but the complete scenario undoubtedly will involve aspects of multiple cluster stellar generations and interior mixing in the stars observed now. Space here does not permit this problem to be explored to the extent that is warranted. As the present paper is not a comprehensive review, the reader is referred to Gratton, Sneden, & Carretta (2004) for an extended discussion and references to prior work on proton-capture abundances.

In this brief overview, we reconsider the abundances of several representative elements that are not susceptible to proton-capture alterations, and hence should reflect only "primordial" cluster nucleosynthetic events (from now-departed high-mass supernovae and intermediate-mass AGB stars). This discussion will begin with comments on general abundance ratio uncertainties, and then update the globular cluster abundance trends discussed in Sneden *et al.* (2004) and Gratton, Sneden, & Carretta (2004).

2. Cluster Abundance Accuracy Limits

At another Paris IAU Symposium nearly two decades ago, Magain (1988) posed a simple but very important question: "Do we intend to continue to provide the galactic evolution theorists with data we cannot reasonably guarantee [reliably], or will we concentrate part of our efforts on checking the validity of our assumptions?" Since that time substantial efforts have been expended on improving all aspects of stellar abundance analysis: greatly augmented laboratory analyses of transition probabilities, hyperfine/isotopic structures, and partition functions; new grids of stellar model atmospheres; increased reliance on synthetic spectra instead of equivalent width computations; and in a growing number of investigations, more realistic (non-LTE) modeling of line formation in 3-dimensional atmospheric models that include granular inhomogeneities. Even with all these improvements, attempts to very accurately define an overall [Fe/H] metallicity scale for globular clusters are still ongoing. In a recent effort to revisit this issue, Kraft & Ivans (2003) derive a metallicity scale based exclusively on abundances derived from Fe II features in 16 well-studied clusters. Their proposed metallicity system is compared with prior work by, in particular, Zinn & West (1984), and Rutledge *et al.* (1997), Rutledge, Hesser, & Stetson (1997b). Their paper considered only those clusters with Ca II infrared triplet data from Rutledge *et al.*, but this work has been expanded by Kraft & Ivans (2004) to give a consistent metallicity scale for a total of 105 globulars. They conclude that it is currently impossible to define an absolute cluster metallicity scale to the 0.05 dex level. Systematic effects applicable to comparisons between different investigations, and to understanding metallicity scale effects beyond study-to-study variations, presently limit defining the globular cluster metallicity scale to no better than $\approx$0.2 dex. Caution should be exercised in chemical evolution studies that require metallicities to better than this figure.

What are the present-day practical reliability limits of abundance ratios, i.e. [M/Fe] values? We have not conducted a thorough study of this issue, but here are some simple ways to view the current state of the art. First, we consider what ought to be a benign case: the [Ni/Fe] ratio. In the uncomplicated yellow-red region spectra usually gathered for globular cluster stars, many lines of Fe I and typically a half-dozen Ni I lines are present. Common nucleosynthetic origins in supernovae are believed to account for these

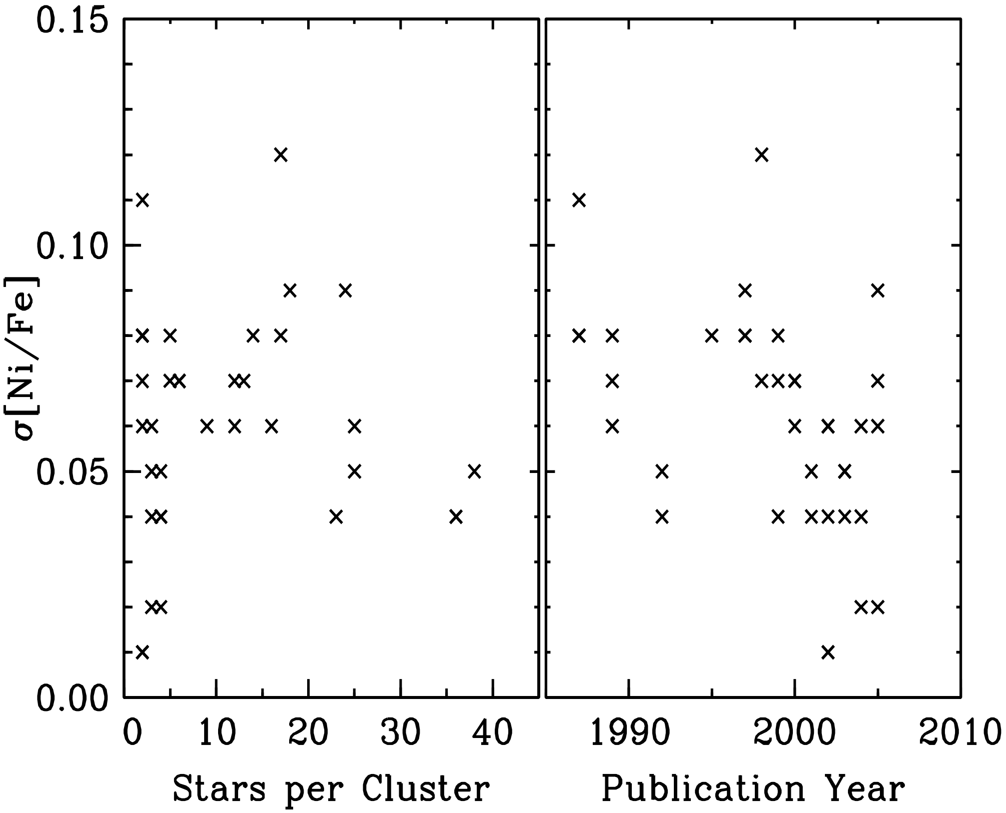

Figure 1. Sample standard deviations σ in [Ni/Fe] values reported for globular clusters in the literature since the advent of echelle/CCD spectroscopy, correlated with the number of stars per cluster and with year of publication.

two elements. Mean [Ni/Fe] values show little cluster-to-cluster variation (this will be revisited in the next section). In Figure 1 we plot the values of σ[Ni/Fe] reported in various cluster abundance studies. These data usually represent the internal abundance variations arising from line-to-line scatter in the Ni I transitions. The cluster data sources are those listed in Table 2 of Gratton, Sneden, & Carretta (2004), supplemented by results for a few other clusters that have appeared subsequently: 47 Tuc, Caretta *et al.* (2004); Pal 12, Cohen (2004); M3 and M13, Cohen & Meléndez (2005a); NGC 7492, Cohen & Meléndez (2005b); and M68, Lee, Carney, & Habgood (2005). This exercise considers only data published since the development of echelle-CCD spectroscopy on 4m-class and larger telescopes. The mean of reported σ[Ni/Fe] is ≈0.06 dex, with little apparent trend as a function of the number of stars observed in a survey (left-hand panel of Figure 1), or of year of publication (right-hand panel).

Next, we consider examples of abundance ratios published in different investigations of two well-studied globular clusters. In the top panel of Figure 2 we plot the results of Sneden *et al.* (2004) and Cohen & Meléndez (2005a) for M3, and in the bottom panel the results of Caretta *et al.* (2004), James *et al.* (2004), and Alves-Brito *et al.* (2005) for 47 Tuc. The optimistic viewpoint would be to note the general agreement among investigators, and simply use the averages of the abundance ratios in each cluster for interpretation. The pessimistic viewpoint would be to note abundances of non-proton-capture elements with apparent substantial disagreements between the studies (Ca, Sc,

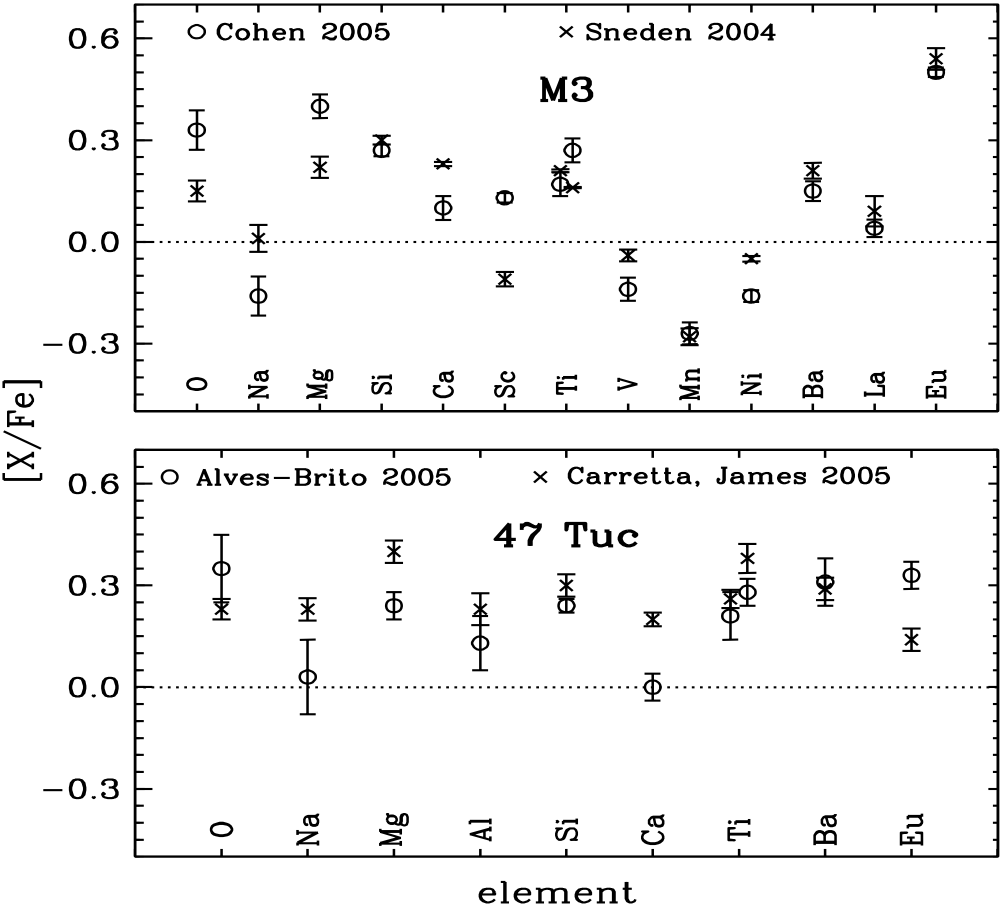

Figure 2. Abundance ratios determined by different studies of globular clusters M3 (top panel) and 47 Tuc (bottom panel). Only elements in common between the compared studies are plotted here. Shorthand literature names are given in the figure. In the top panel, Cohen 2005 is Cohen & Meléndez (2005a) and Sneden 2004 is Sneden *et al.* (2004) In the bottom panel, Alves-Brito 2005 is Alves-Brito *et al.* (2005), Carretta, James 2004 is Caretta *et al.* (2004) for elements O through Ti and James *et al.* (2004) for Ba and Eu. Note that Ti is represented by both Ti I and Ti II abundance results. The error bars in this figure are the standard deviations of the means.

V, Ni for M3, Ca and Eu for 47 Tuc), and conclude that accuracy to better than ≈0.1 dex in abundance ratios is difficult to achieve at present. The total abundance uncertainties of course must include internal (line-to-line scatter) and external (scale) errors. In Figure 1 we were concerned only with the internal part of the total. However, with many globular cluster abundances still represented by analyses of only a handful of stars, the star-to-star scatter still is a significant part of the overall uncertainty.

The scale errors have many possible origins, but comment here will be made only on effects of line selection and associated transition probability uncertainties. Different abundance studies often employ different transitions for the various elements, sometimes by choice but often through necessity. To take one easy example, the Na I doublets near 5685 and 6145 Å are often the transitions of choice for globular cluster Na abundances. But at the lowest metallicity end ([Fe/H] ∼–2.5) of the cluster system, these transitions become very weak, and in some studies the Na abundances are derived with the much stronger Na D lines (these are the only detectable Na I features in ultra-metal-poor field stars). The D-lines are usually saturated when the higher excitation lines are useful for abundance work. Additionally, their formation is subject to significant and as yet uncertain departures from LTE as summarized by Ivans *et al.* (these Proceedings). Thus at present it is difficult to compare abundance results from the various available Na I features.

Even when studies employ the same transitions, the adopted transition probabilities can contribute substantially to the abundance error budget. In the wavelength domain of interest to cluster abundance surveys, 4000 Å $< \lambda <$ 9000 Å, new laboratory gf values have been published for many species. However, a substantial fraction of these papers has been devoted to neutron-capture elements, rare earths in particular (e.g., den Hartog *et al.* 2005, and references therein). Many neutral species of Fe-peak and lighter elements, such as Mg I, Si I, and Sc II, would greatly benefit from renewed attention by the atomic physics community. Only when the transition probability data are more secure for such elements can studies of globular clusters abundance trends be placed on firmer footing.

3. Some Cluster and Field Star Abundance Trends

In Sneden *et al.* (2004) and Gratton *et al.* (2004) comparisons were made between the abundance ratios of globular cluster stars and members of the halo field. In Figure 3, the plots from those papers on Ni and the α element Ca are updated with abundances reported in the new studies named in the preceding section. Also included for Ca are abundances based on one Ca I line detected in infrared spectra of the Galactic bulge clusters Terzan 4 and Terzan 5 obtained by Origlia & Rich(2004). Caution must be given about possible offsets between this Ca I line and the ones in the visible spectral region usually employed in cluster work. However, any efforts to push abundance studies out to the IR are welcome. This will be the only practical way to obtain data on the more heavily reddened disk clusters, and further such studies are to be encouraged.

For both Ni and Ca, the general conclusions from the earlier compilations are unchanged by the addition of newer data: to the limit of present observational uncertainties, the abundance ratios of field and cluster stars are virtually identical over the metallicity range –0.5 > [Fe/H] > –2.5. There are some interesting exceptions. Most notably are the clashes in [Ni/Fe] and [Ca/Fe] between the vast majority of the objects and the halo clusters Ruprecht 106 and Pal 12. In Figure 3 we specially mark the abundance of these elements determined in the pioneering study of Brown *et al.* (1997), which claimed that both clusters have anomalously low α-element abundances. The higher resolution, higher signal-to-noise larger-sample study (four stars instead of two) of this cluster by Cohen (2004) derives an even lower Ca abundance than did Brown *et al.* (1997), and also appears to remove the low-Ni anomaly of the prior study. As a final comment on this figure, attention is directed to the persistent overabundances of Ca in clusters at highest metallicities. Indeed, a straight line could be drawn through all the cluster data at [Ca/Fe] $\approx$+0.3 ± 0.1, with no trend in [Fe/H]; very few cluster points would lie outside this band. Future studies should be directed to confirming the reality of the apparent cluster/field disagreement at [Fe/H] > –0.5.

In Figure 4 we display similar plots for three elements that have readily detectable features in globular cluster giants: Ba and La (most easily synthesized in s-process neutron-capture reactions), and Eu (most easily synthesized in the r-process). Note that only a small number of transitions of these elements are detectable in the yellow-red spectra of globular cluster giants: 3 for Ba II, 1-2 for La II, and only 1 for Eu II. This should be kept in mind when considering the heightened star-to-star scatter of this figure compared to Figure 3. Also, note that the new Cohen (2004) Pal 12 analysis confirms the

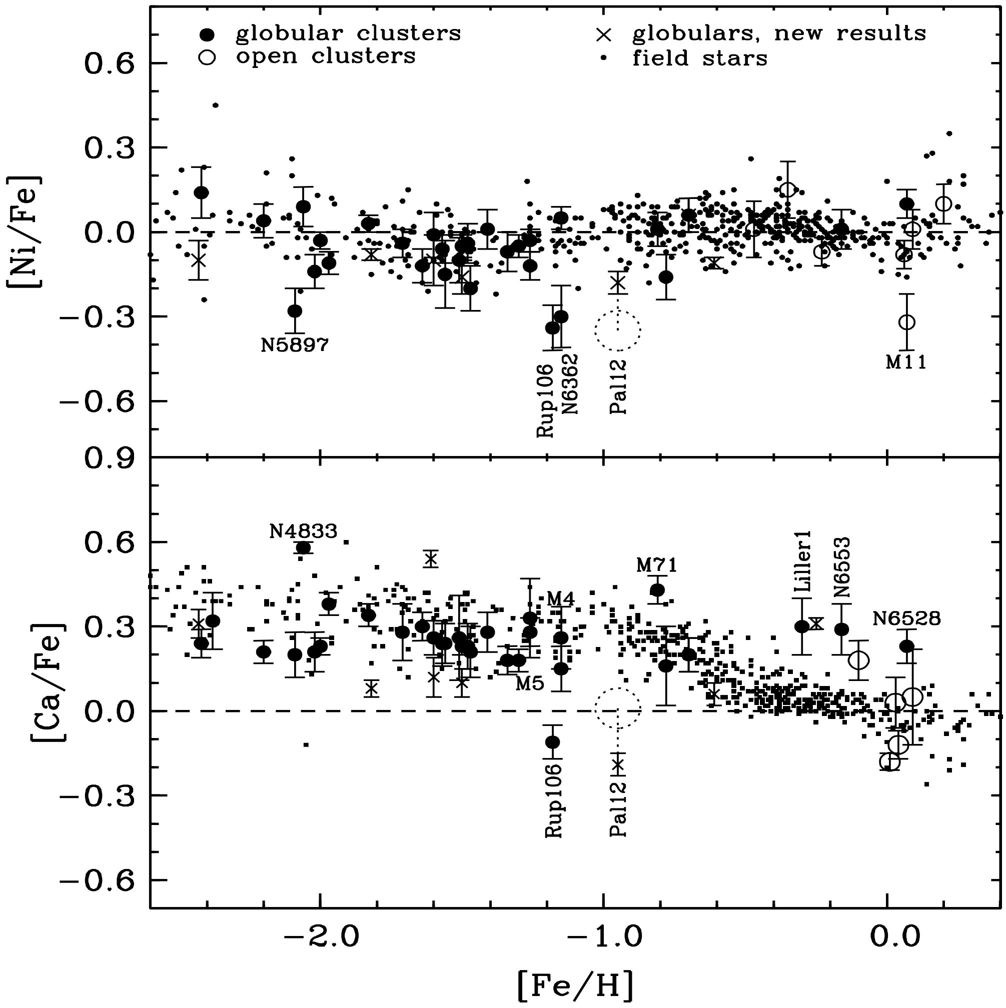

Figure 3. Relative Ni and Ca abundances plotted with respect to Fe metallicity for cluster and field stars. The data for field stars and open clusters are unchanged from Gratton, Sneden, & Carretta (2004), to which the reader is referred for the original literature sources. Data for several clusters with new or improved abundances are plotted with "x" symbols. Special note is given to Pal 12, for which the recent study of Cohen (2004) ("x") has superseded that of Brown *et al.* (1997) (large dotted circle connected by a vertical line to the "x"). A few clusters that apparently do not share the general patterns of most halo and cluster stars are named in the figure. The abundances as reported in the literature have been adopted without change; no attempt has been made to use only abundances derived from the same lines in the various studies.

values for these elements determined by Brown *et al.* (1997). The essential message here is the same, however. The material of Galactic halo cluster and field stars clearly experienced similar nucleosynthetic histories. The same relative dominance of r- over s-process neutron-capture events exists for all halo constituents.

4. Concluding Remarks

The Galaxy contains about 150 globular clusters, but detailed chemical composition analyses with even modest-sized samples (>5 stars) have been published for at most a

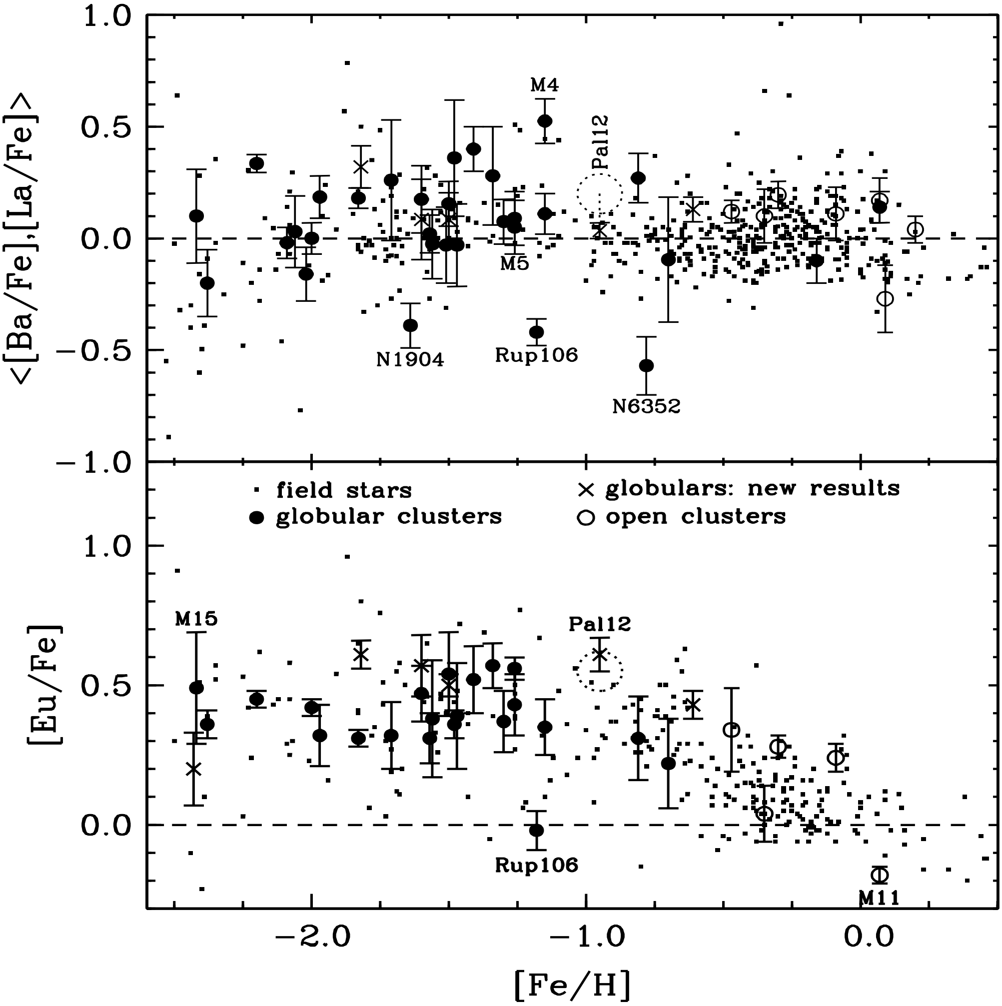

Figure 4. Relative abundances easily-observed neutron-capture elements Ba, La (top panel) and Eu (bottom panel) plotted with respect to [Fe/H] metallicity. All symbols are as in Figure 3. Since Ba and La are usually synthesized with equal efficiency in (mostly) the *s*-process, when both are reported for a star their abundances have been averaged.

third of these. Happily, several groups are working hard to significantly expand this sample. These efforts are to be applauded, as are the studies that combine data over a larger luminosity (hence evolutionary) range, e.g. Caretta *et al.* (2004), Cohen & Meléndez (2005a), Boesgaard *et al.* (these Proceedings). Hopefully within a few years meaningful trends will be established in abundances not only with metallicity but with Galactocentric distance, as has been explored by Lee & Carney (2002), Stephens & Boesgaard (2002), and Fulbright (2004). A parallel major undertaking must be to merge these future results and to put them on common, reliable abundance scales. Only in this manner can the observed abundances meaningfully confront models of Galactic chemical evolution.

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Jennifer Sobeck, chaired by Matthew Shetrone.

Verne Smith talking about fluorine in globular clusters.

Roger Cayrel and François Spite at the welcome reception.