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The relationship between globular cluster parameters and abundance variations

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Abstract. We discuss a meta-analysis of the association of abundance variations in globular cluster stars with the present-day stellar mass and metallicity of globular clusters. Using data for 42 globular clusters that are well-sampled from either or both of prior literature studies and the APOGEE survey, we confirm prior findings that increasing aluminum abundance variations in globular clusters are positively correlated with increasing present-day stellar mass or decreasing metallicity. We also demonstrate that the ratio of aluminum abundance variations to either nitrogen abundance variations or sodium abundance variations is itself positively correlated with decreasing metallicity and increasing stellar mass of globular clusters. This suggests that there were at least two non-supernovae chemical polluters that were active in the early universe.

Keywords. Globular Clusters

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1. Introduction

Globular clusters are now thoroughly demonstrated to host stars with correlated variations in their light-element abundances, such as those of He, C, N, O, Na, Al, Mg, which can be characterized as being associated with "multiple populations" (Carretta *et al.* 2009; Pancino *et al.* 2017; Masseron *et al.* 2019).

In addition to the above references, this phenomenon is one of the major topics at this conference, being mentioned in at least fifteen of the talk titles. There is interest in both of empirically describing the multiple populations in the chemical and kinematic spaces, and in understanding and explaining their origins. At this time, there are several models seeking to attempt to explain the nature and presence of multiple populations, but none are successful in matching all available constraints. This theoretical challenge has recently been reviewed by Renzini *et al.* (2015) and Bastian & Lardo (2018). A solution will likely require advances in each of our understanding and modelling of gas physics, star formation, the initial mass function, nucleosyntheic yields, among other areas.

In this proceeding, we describe the results and potential applications of a meta-analysis of stellar abundance variations in globular clusters (Nataf *et al.* 2019) measured both by prior literature studies and by the APOGEE survey (Majewski *et al.* 2017), and how these abundance variations are associated with the global parameters of globular clusters.

2. Data

The meta-analysis of Nataf *et al.* (2019) included spectroscopic data from the APOGEE spectroscopic survey (Majewski *et al.* 2017). The field contamination of the globular cluster sample is decreased by matching candidate members of globular clusters to Gaia proper motion data (Gaia Collaboration *et al.* 2018) and comparing these to the globular cluster structural and dynamical parameters determined by Baumgardt & Hilker (2018) and Baumgardt *et al.* (2019). We also used a metallicity prior from Harris (1996, 2010

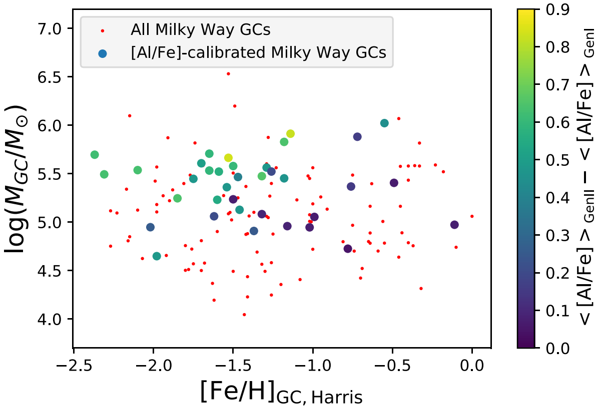

Figure 1. Figure 16 from Nataf *et al.* (2019). Globular clusters with a lower [Fe/H] or a greater stellar mass tend to have a greater difference in the mean aluminum abundance of their multiple populations. The 36 clusters with measurements of mean aluminum enrichment are color coded between dark blue and yellow respectively corresponding to small and large mean differences in [Al/Fe]. The clusters without measurements are shown as the small red points. Colour version available in online edition.

edition). The precise delineation of this selection function can be found in Section 2 of Nataf *et al.* (2019). This selection yielded a sample of 1,051 stars from 38 globular clusters. The three abundances that were relevant to the study of the APOGEE data were [Fe/H], [N/Fe], and [Al/Fe].

Separately, literature data for 34 globular clusters were used as part of the meta-analysis, see Table 5 of Nataf *et al.* (2019). The three abundances that were relevant to the study of the literature data were [Fe/H], [Na/Fe], and [Al/Fe].

3. Aluminum abundance variations and globular cluster parameters

The abundances of several light elements can vary among stars of the same globular clusters, including those of the s-process elements (Marino *et al.* 2009), potassium (Cohen & Kirby 2012), fluorine (D'Orazi *et al.* 2013), and lithium (D'Orazi *et al.* 2015).

The study of Nataf *et al.* (2019) focused on sodium, nitrogen, and aluminum as these were the elements whose abundances that were most likely to be consistently measured. Sodium and/or nitrogen were used to separate the stars of globular clusters into their different chemical subpopulations. The difference in [Al/Fe] between the different subpopulations was then quantified, and correlated with other globular cluster parameters.

3.1. *The mean difference in [Al/Fe] between chemically normal and chemically anomalous globular cluster stars*

A global attempt at evaluating these associations can be found in Figure 1. The scatter of the metallicities and stellar masses (from Baumgardt & Hilker 2018 and Baumgardt *et al.* 2019) of the Milky Way's globular clusters are plotted. The 36 clusters for which we could reliably determine the difference in the mean aluminum abundance of the chemically “normal” and “anomalous” populations are plotted in relatively large coloured points.

Clusters for which the enhancement in [Al/Fe] is null or negligible appear as dark blue points, they are found predominantly at low masses and at higher metallicities. The converse holds for clusters with large enhancements in [Al/Fe]. This builds on the results

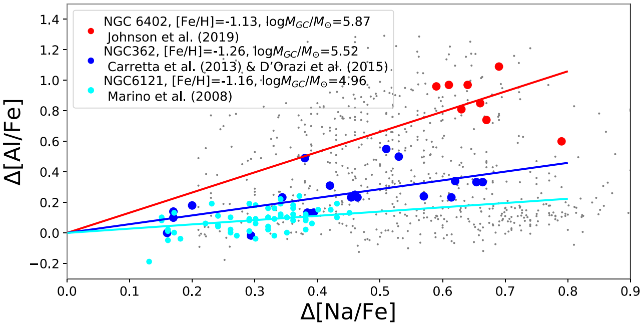

Figure 2. The relationship between nitrogen and aluminum enhancement in three different clusters with similar metallicities and very different masses. We can see that at approximately fixed metallicity, the enrichment of aluminum is proportionately higher relative to that of sodium. Colour version available in online edition.

of Carretta *et al.* (2009) and Pancino *et al.* (2017), who have also identified this bivariate correlation, though with smaller samples.

3.2. *The ratio of enhancement in [Al/Fe] to that of [N/Fe] or to that of [Na/Fe]*

The measurement of the mean variation in [Al/Fe] is an instructive diagnostic, but in practice, chemical abundance variations among globular clusters typically are distributed along along vectors, and that is how they should be modelled.

We thus fit for the mapping of the variation of Δ[Al/Fe] versus Δ[Na/Fe] or Δ[N/Fe] as a function of $[\mathrm{Fe/H}]_{\mathrm{GC}}$ and $\log M_{\mathrm{GC}}/M_\odot$. We found that an increasing values of Δ[Al/Fe]/ Δ[Na/Fe] or Δ[Al/Fe]/Δ[N/Fe] were positively correlated with decreasing $[\mathrm{Fe/H}]_{\mathrm{GC}}$ and increasing $\log M_{\mathrm{GC}}/M_\odot$ with a few caveats. The value of Δ[Al/Fe] appears to never be negative, and there is a maximum amplitude to the metallicity effect.

As an example of the mass effect, we plot the scatter of Δ[Al/Fe] versus Δ[Na/Fe] for three densely-sampled globular clusters with nearly identical metallicities but very different stellar masses in Figure 2. These are the clusters NGC 6121 / M4 (Marino *et al.* (2008)); NGC 362 (Carretta *et al.* 2013; D'Orazi *et al.* 2015); and NGC 6402 Johnson *et al.* (2019). The higher the present-day stellar mass of the cluster, the higher the slope of Δ[Al/Fe]/Δ[Na/Fe].

4. Implications and Conclusions

In this proceedings, we have reviewed a meta-analysis (Nataf *et al.* 2019) of aluminum abundance variations in globular clusters from both prior literature and ongoing APOGEE data, and the association with globular cluster parameters.

We have confirmed prior findings that increasing spread in aluminum abundance is positively correlated with increasing present-day stellar mass and decreasing metallicity (Carretta *et al.* 2009; Pancino *et al.* 2017; Masseron *et al.* 2019). We have also shown that the *ratio* of aluminum enrichment to either nitrogen enrichment or sodium enrichment is itself positively correlated with increasing stellar mass and decreasing stellar metallicity.

We note that the association between metallicity and aluminum abundance variations is a prediction of the "assymptotic giant branch (AGB) model" of multiple populations of globular clusters, which is adequately described in the reviews by Renzini *et al.* (2015) and Bastian & Lardo (2018). In that model, the conversion of magnesium into aluminum via the $^{24}\mathrm{Mg}(\mathrm{p},\gamma)^{25}\mathrm{Al}$ reaction is decreased at higher metallicities, due to the lower likelihood of stellar interiors reaching the necessary minimum temperature of

$T \approx 8 \times 10^7\ K$ (Lattanzio *et al.* 2000; Ventura *et al.* 2016; Dell'Agli *et al.* 2018). The anticorrelation between increasing aluminum abundance variations and increasing metallicity is thus predicted, and can be seen as a success of that model. However, the correlation with globular cluster mass is *not* predicted by that model, and thus we may conclude that the AGB model is not a complete descriptor of the formation of multiple chemical populations in globular clusters. These trends, taken together, necessitate the presence of at least two non-supernovae chemical polluters to have been active in the early universe, plausibly including AGB stars. It is likely that both polluters contribute to each of CNO, NeNa, and MgAl nuclear processing, but that the second polluter contributes proportionately more to the MgAl processing, and is proportionately more important in systems that evolve to being higher mass globular clusters.

It will be interesting to integrate other stellar abundance variations of globular clusters into this framework. It is not known how many independent components there are, but that could be constrained by acquiring a large sample of homogeneously-derived abundances for a larger set of elemental abundances.

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