Globular Clusters and the Milky Way Connected by Chemistry

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There are two ways to study galaxy formation and evolution: one is to observe a large number of galaxies at a variety of redshifts, the other is to observe in detail just a few nearby galaxies. The precision achievable by the latter method enables the galactic history, including the formation and early evolution, to be studied. Globular clusters provide targets for the second method. We show how the chemical content of Milky Way globular clusters can be used to place them on a timeline charting the history of our Galaxy. The results suggest that different α-elements trace different processes of Milky Way chemical evolution.

The seminal work of Eggen, Lynden-Bell & Sandage (1962) was the first to use stars as tracers of the history of the Milky Way. They found that older metal-poor stars have more elliptical orbits while younger metal-rich stars move in circular paths. They concluded that the proto-Milky Way had collapsed by the time of the formation of the first stars and a few hundred million years later the collapsed gas achieved circular motion and formed new stars. This was the beginning of the field now called galactic archaeology.

Another important step was provided by Searle & Zinn (1978), who found no trace of a radial metallicity gradient for the halo globular clusters, and suggested that halo globular clusters formed in protogalactic fragments that were accreted to build the Milky Way halo, after the collapse of the Bulge. Since then many works have been devoted to the use of globular clusters in the study of galactic archaeology. In particular, with the advent of telescopes in space, and larger ground-based telescopes, such studies are able to spatially resolve stars in these clusters and also to obtain spectra of individual stars, even for the most distant clusters. Saviane et al. (2012) present a summary of this work. Figure 1 illustrates the current capacity to observe individual stars in clusters in a broad context.

Digging into the clusters

Almost 40 years after the work of Searle & Zinn, it is legitimate to ask what there is left to study. In many investigations that followed Searle & Zinn, astronomers observed the integrated light of all the globular cluster stars, which can be contaminated by non-cluster members and does not provide information on, for example, any star-to-star chemical abundance variations. Nowadays it is well known that stars in most globular clusters are split into at least two generations, evident from variations in the abundances of light-elements such as Na, O, Mg, Al, C, N. Further, we now know that bright horizontal branch stars can be bluer or redder depending on their He abundance. The current challenge is to find a model that connects the variations in Na, O, Mg, Al, C and N with the variation in He. Age and total metallicity also play a role in determining horizontal branch morphology (see reviews by Gratton et al., 2004, 2012). Therefore, in order to understand the formation of stars in globular clusters, it is clearly important to derive chemical abundances of individual cluster stars.

However, only about 60% of Milky Way globular clusters (of which 157 are currently known [Harris, 1996]) have had their metallicities derived on a homogeneous scale based on consistently obtained integrated or resolved spectroscopy. But only ~ 50% of these determinations are based on spectroscopy of individual

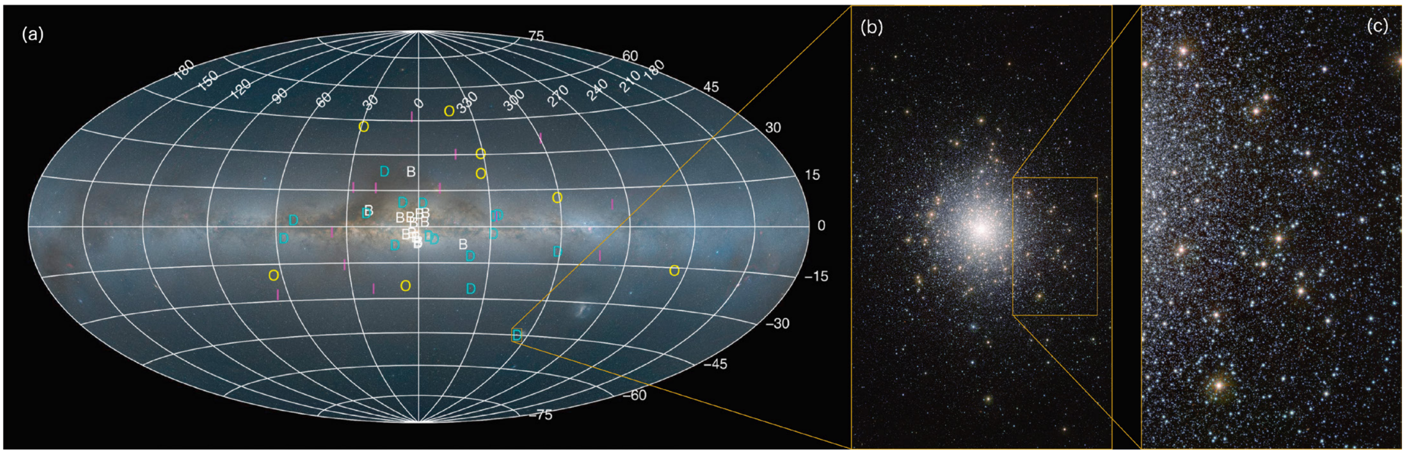

Figure 1. (a) All-sky view centred on the Milky Way Plane in an Aitoff projection from Mellinger (2009) with a Galactic coordinate grid. The globular clusters studied here are identified by letters according to their populations, namely (B)ulge, (D)isc, (I)nner halo, and (O)uter halo. (b) Zoomed-in image of the globular cluster 47 Tucanae (near-infrared image taken with VISTA: ESO image eso1302a), which can be seen with the naked eye in a dark sky. (c) Detail from the same image as (b) of an outer region of 47 Tucanae, showing its brightest bluer and redder stars; the latter stars were analysed in this work.

stars (Carretta et al., 2009). Furthermore, high-resolution spectroscopic metallicities are available for only ~ 25 % of them (Pritzl et al., 2005). Not only is this number of clusters low but the sample is biased, given that it includes only a few metal-rich Bulge clusters.

We selected 51 globular clusters that represent well the Milky Way Bulge, Disc, and Halo populations, and which cover the full range of metallicity, total mass, distance and reddening values, in order to increase the statistics and generate an unbiased sample. In particular, the cluster red giants in half of our sample are very faint owing to substantial foreground dust or large distances, and are therefore poorly studied (Dias et al., 2016). The present work increases to ~ 70 % the fraction of clusters with known spectroscopic metallicity derived on the same scale.

High-resolution spectroscopic observations would be too time-consuming if devoted to the sample of about 800 red giant stars in 51 globular clusters that we have studied, especially for the fainter targets. We instead used a lower resolution (R ~ 2000) spectrograph, which consequently allows higher signal-to-noise ratios to be achieved with lower integration times. This approach also enables us to observe more targets and have a more complete sample, including fainter targets. For the analysis we were able to apply full-spectrum fitting that is intrinsically reddening-free (Dias et al., 2015). The method has the advantage that it can be applied to red giants in extragalactic globular clusters in the future.

FORS2 data

The FOcal Reducer / low dispersion Spectrograph (FORS2) in its medium-resolution and multi-object mode (Appenzeller et al., 1998) is consequently more suitable for our purposes than the Fibre Large Array Multi Element Spectrograph (FLAMES) facility (Pasquini et al., 2002) combined with the Ultra-violet Visible Echelle Spectrograph (UVES). The first question that arises is: are we losing precision in the determination of chemical abundances with this choice? We were able to derive metallicities from FORS2 spectra in very good agreement with UVES metallicities for the globular clusters in common: the root mean square of the differences is within 0.08dex and presents no trend with abundance. Therefore there is no need to re-calibrate our FORS2 results (Dias et al., 2016).

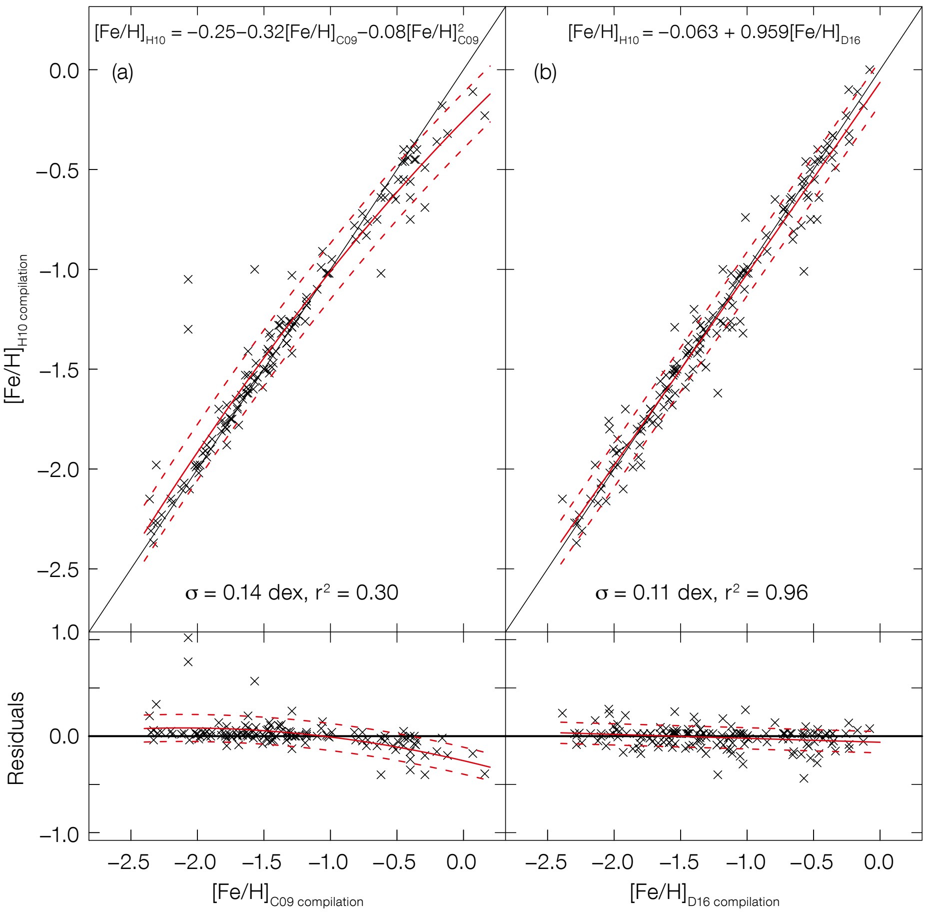

Figure 2. (a) Comparison of metallicities of 132 clusters common to the metallicity scales of Carretta et al. (2009) and Harris (1996), C09 and H10 respectively. The best fit and 1σ limits are shown by red continuous and dotted lines, respectively. (b) The same as (a) but for 151 clusters common to our abundance scale (Dias et al., 2016a) and that of Harris (1996). Details of the fits are given in each panel.

Carretta et al. (2009) applied their metallicity scale, based on UVES data, to all previous sets of cluster metallicity and averaged them. Their scale is limited in the metal-rich tail because they did not observe clusters in this regime. Harris (1996) produced a compilation of cluster metallicities based on spectroscopy and photometry, and made an effort to put them all on a homogeneous scale, similarly to Carretta et al. We followed the same steps, with the advantage that we have 51 clusters in our sample (compared to 19 for Carretta et al.) as references for scaling previous work. Importantly, our clusters cover the full metallicity range: the catalogue of globular cluster abundances can be downloaded[1]. Figure 2 shows good agreement between our compilation of abundances and those from Harris, with a mild linear trend that should be applied to the Harris (1996) values. The comparison with Carretta et al. confirms the discrepancy for the metal-rich clusters as expected, and reveals a few outliers. We have increased the fraction of clusters with known (spectroscopic and photometric) metallicities from 84 % (Carretta et al.) to 97 % of the total Milky Way globular cluster sample, improving coverage of the metal-rich tail.

Field versus cluster stars

It has been known for quite some time that the ratio of α-elements over iron [α/Fe] is larger at the beginning of a galaxy's life, as a result of early chemical enrichment by core-collapse supernovae. Some time later, estimated to be around 0.5 to 2 Gyr, thermonuclear type Ia supernovae produce large amounts of iron, which causes [α/Fe] to decrease. The time when the second event starts to be important is a key piece of information for understanding the efficiency of star formation in a galaxy. In the case of the Milky Way, the chemistry of field stars indicates a timescale of about a billion years as indicated by the depletion in [α/Fe] (e.g., Matteucci & Recchi, 2001). Nevertheless, not all α-elements are expected to behave in the same way. For example, the lighter element magnesium is produced in hydrostatic phases of massive star evolution, whereas the heavier elements calcium and titanium result from explosive nucleosynthesis (see, for example, McWilliam, 2016). If we compare the nucleosynthesis yields from core-collapse and thermonuclear supernovae, the contrast of [Mg/Fe] between the two episodes is larger than the contrast of [Ca/Fe] and [Ti/Fe] (Pagel, 1997).

This difference is noticeable in field star distributions, but globular clusters seem to have a constant [Mg/Fe] and [<Mg,Ca,Ti>/Fe] ratio for any given metallicity, despite their age range of a few billion years (see the literature compilation by Pritzl et al., 2005). A possible reason for the disparity is that the thermonuclear supernovae that affected field stars did not occur before all stars in globular clusters were formed. Our homogenous abundances for 51 clusters suggest the different trends of [Mg/Fe] and [<Mg,Ca,Ti>/Fe], as expected.

It is important to point out that many of the α-elements are electron donors, and their excess adds electrons, and therefore H^- opacity. Besides the true α-elements, Al behaves as an α-element in the Galactic Bulge, being an important electron donor. Such effects have to be taken into account when computing abundances in stellar atmospheres, as done in Coelho et al. (2005) whose approach we adopted. Possibly the high dispersion of α-element abundances from Pritzl's compilation was hiding trends that are now revealed by our results with lower dispersion (see Figure 3). Our contrasting results beg the question: is chemical enrichment by supernovae for field and cluster stars correlated?

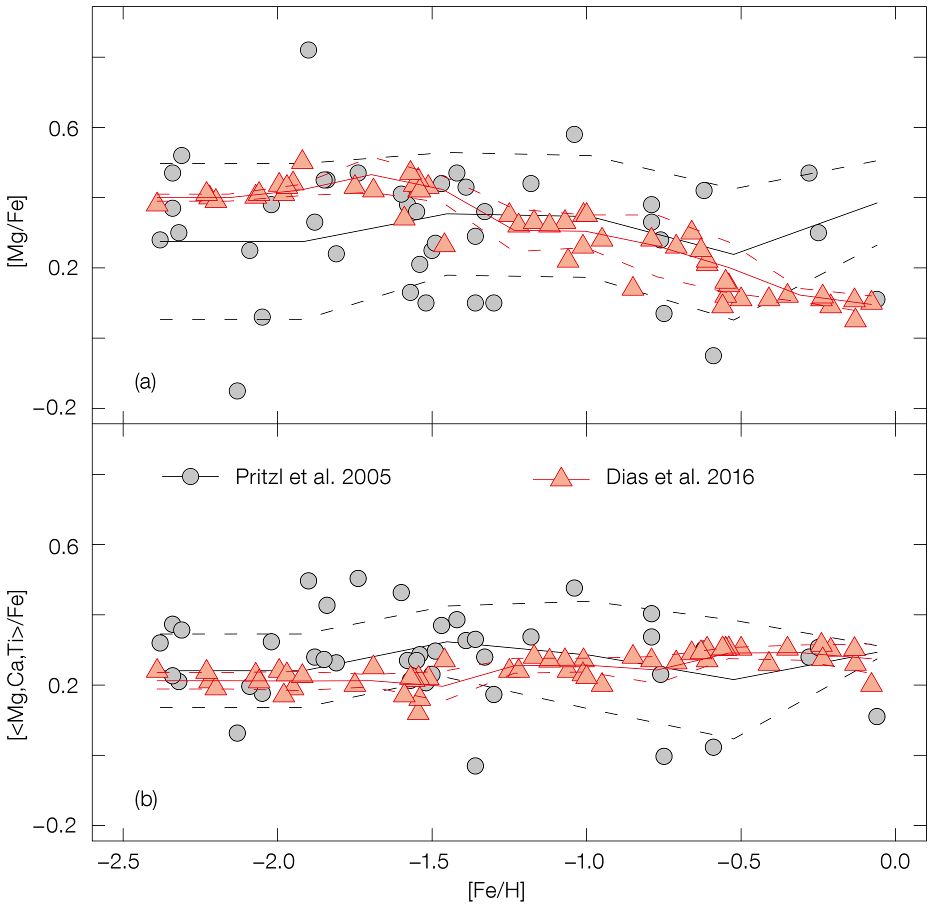

Figure 3. (a) Distribution of enhancement of magnesium versus total metallicity for globular clusters from Pritzl et al. (2005) in grey (with the fit shown by a black line and the 1σ error bands by dashed lines), contrasted with our results (Dias et al., 2016) in pink (with fit and error bounds as red solid and dashed lines, respectively). (b) Same as (a) but for the average of enhancements of three α-elements: magnesium, calcium, and titanium.

Extragalactic globular clusters

Since our strategy of employing low-resolution spectroscopy has succeeded for faint stars in distant and highly reddened Milky Way clusters, we can certainly follow the same steps to observe red giants in nearby galaxies to understand their formation and early evolution using a similar array of techniques. In the era of extremely large telescopes, this strategy can be extended to many nearby galaxies.

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Links

[1] Access to catalogue of abundances: http://www.sc.eso.org/~bdias/catalogues.html