Observations of Multiple Stellar Populations in Globular Clusters with FLAMES at the VLT

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In the last few years, it has become evident that globular clusters, previously accepted as prime examples of simple stellar populations, contain at least two, and in some cases more, stellar generations. Thanks to the superb spatial resolution of the Hubble Space Telescope on one side, and to the forefront spectroscopic and multiplexing capabilities of UVES and FLAMES at the VLT on the other, extensive, high precision datasets are shedding light on cluster formation and evolution. Here, we briefly describe the contribution by our team to these exciting discoveries.

Figure 1. Image of the globular cluster 47 Tuc (NGC 104), obtained with the ESO 1-metre Schmidt Telescope at the La Silla Observatory in Chile.

Multiple populations in globular clusters

Globular clusters (GCs) are very massive stellar complexes. As an example, Figure 1 shows an image of the globular cluster 47 Tucanae. All GCs observable in or near the Milky Way are very old, so their formation cannot be observed in detail. These early phases were likely complex, including a variety of dramatic and energetic phenomena such as supernova (SN) explosions, photoionisation, high and low velocity winds from blue and red massive stars, possibly combining in giant expanding bubbles of gas and shock fronts that may have triggered further star formation. The scene where this drama occurred might have been even more diversified — in the core of giant clouds or, for the most massive clusters, even of dwarf galaxies. These dramatic events left a trace — represented by the chemical composition of the stars — that not only can be followed today in quite subtle spectral features, but also can influence their distribution along the main sequence (MS) and the horizontal branch (HB).

All GCs investigated to date show a peculiar abundance pattern (for a review, see Gratton et al., 2004). They usually appear to be very homogeneous, with a few exceptions like M 54 and Omega Centauri, insofar as the Fe-peak elements are concerned, thus ruling out self-enrichment by SN ejecta. However, many GC stars have an unusual composition, rich in Na and Al and poor in O and Mg, typical of material that experienced H-burning at very high temperatures, while others have a normal O- and Mg-rich but Na- and Al-poor composition, which is virtually identical to that of metal-poor field stars. Within each GC, the abundances of Na and O, or Al and Mg are anti-correlated with each other (see Figure 2). Since the main outcome of H-burning is He, we expect low O/high Na stars also to be He-enriched, which explains the occurrence of multiple HBs and MSs. The connection between O–Na and Mg–Al anti-correlations, variations in He abundances, and the presence of multiple HBs is however likely to be more complex than described here (see Gratton et al., 2010).

This abundance pattern between O–Na and Al–Mg is characteristic of GCs, while it is almost absent among field stars (Gratton et al., 2000). It is not limited to red giants, but is present also in the low-mass MS stars, as demonstrated by the key study with the VLT's high resolution optical spectrograph, UVES, by Gratton et al. (2001; based on the large programme 165.L-0263). These unevolved stars cannot have sustained the nucleosynthesis chains that deplete O and Mg, and enhance Na and Al, because they cannot reach the required temperatures and have very thin convective envelopes, unable to mix nuclear products into their atmospheres. The UVES large programme excluded early claims that this composition might result from a peculiar evolution of GC stars: all low O/high Na stars originated from matter processed and ejected by stars belonging to a previous stellar generation within the GC, although not by the SNe (or the low-mass stars, which give a different characteristic imprinting) of this earlier population.

Self-pollution models still lag behind the observations and are not yet able to explain convincingly all observed features: candidate first generation (FG) polluters are either thermally pulsating intermediate-mass asymptotic giant branch (AGB) stars undergoing hot bottom burning (Ventura et al., 2001) or massive rotating stars prior to SN explosion (Decressin et al., 2007).

Our FLAMES survey

Although the star-to-star O–Na abundance anticorrelation had been recognised early on as a pivotal signal of self-enrichment in GCs, significant progress was hindered by the slow acquisition rate of data, due to the use of single object spectrographs. At the time of the Gratton et al. (2004) review, data for a grand total of only about 200 stars, distributed in some ten GCs, were available. The high multiplexing capability of the VLT's Fibre Large Array Multi Element Spectrograph (FLAMES) allowed us an order of magnitude increase in data collection capability: our survey has already harvested spectra for more than 2000 red giants, analysed individually with a homogeneous procedure. With our work, we intended to answer some fundamental questions: Were GC stars really born in a single instantaneous burst? Did all GCs self-enrich themselves? How do abundance patterns within each individual GC relate to the formation and early evolution of the GC itself and of each individual member?

We selected a large sample of GCs with diverse HB morphology, since, as mentioned, there appears to be a link between the chemical anomalies, the extension of the HB, and the presence of multiple MSs. We obtained FLAMES data on 24 GCs (ESO programmes 072.D-0507, 073.D-0211, 081.D-0286, and 083.D-208). We used the pipeline-reduced spectra to obtain Fe, Na, and O abundances from spectra from the medium-high resolution spectrograph, GIRAFFE, and of more elements, including Mg and Al, from the UVES data. Up to now we have published about 15 refereed papers presenting results for 21 GCs.

With this data, we have confirmed that all GCs contain multiple populations (Carretta et al., 2009a). We even proposed a new definition of *bona fide* GCs as "stellar aggregates showing the Na–O anticorrelation", as distinct from associations and open clusters (Carretta et al., 2010a). In Figure 3, adapted from Carretta et al. (2010a), we show massive stellar clusters (both GCs and open clusters) in the relative age *vs*. mass plane. Here relative ages are used (see Carretta et al., 2010a): in this scale, a relative age of 1 means an age close to 12.5 Gyr. Different symbols are used for open clusters and GCs, and for those clusters where the Na–O anticorrelation has been found or not (for several clusters, data currently available are not sufficient to clarify this point). From this figure, it seems clear that the presence of multiple populations is the typical result of the formation process of massive stellar clusters and must be explained by their formation scenarios.

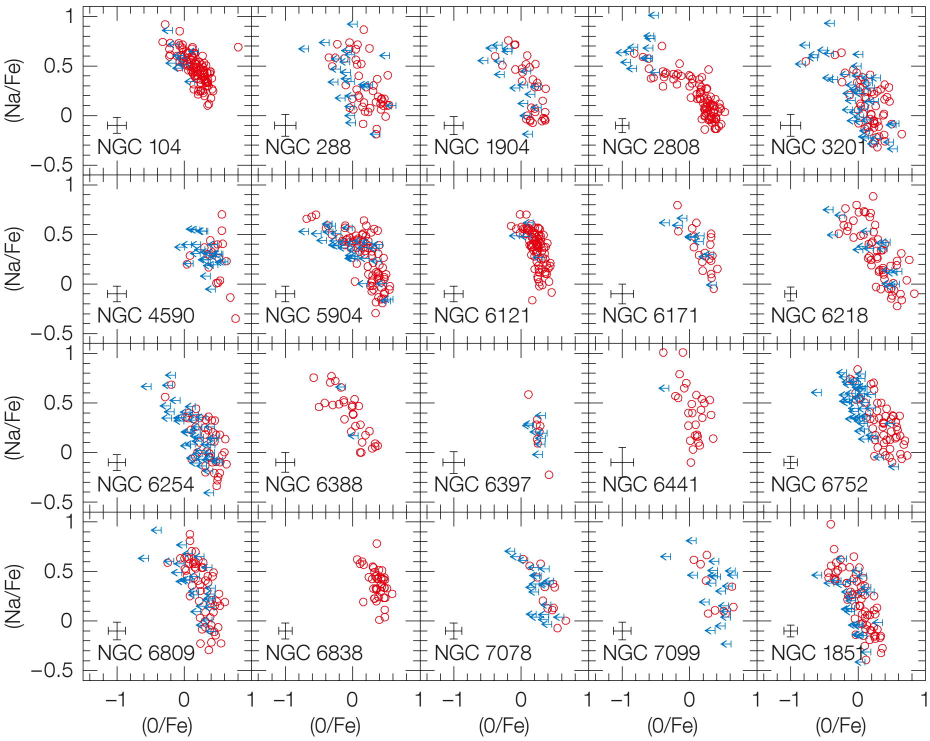

Figure 2. The Na–O anticorrelation is shown as log*(Na/Fe) vs*. log*(O/Fe)* normalised to the solar abundance in 20 GCs as observed with FLAMES (adapted from Carretta et al. [2009a] and Carretta et al. [2010]). The typical error bar for each set of measurements is shown.

The size of our sample led, for the first time, to a quantitative estimate of the fraction of FG and second generation (SG) stars in GCs (Carretta et al., 2009a). The SG is always dominant, including at least two thirds of the total population. Since the peculiar chemical composition of the SG stars indicates that only a fraction of FG stars may have produced the right gas mixture, the original clouds from which the GCs formed should have been much more massive than current GCs (likely ten times or even more). Since GCs now account for roughly 1 % of the Galactic halo, a large fraction of the halo should have originated in the same episodes that led to the formation of the GCs.

We obtained diverse distributions of the Na–O and Mg–Al anticorrelations for different GCs (Carretta et al., 2009a, Figure 2; Carretta et al., 2009b) in some of the GCs, indicating that some parameter, most likely the typical polluter mass, is varying from cluster to cluster. There is a strong link between the extension of the Na–O anticorrelation and some of the main parameters of GCs, mainly mass and metallicity.

We also confirmed that in spite of these striking star-to-star differences in the light elements, most GCs (with a few notable exceptions) are extraordinarily homogeneous in Fe-peak elements, with upper limits as low as 5 % on the root

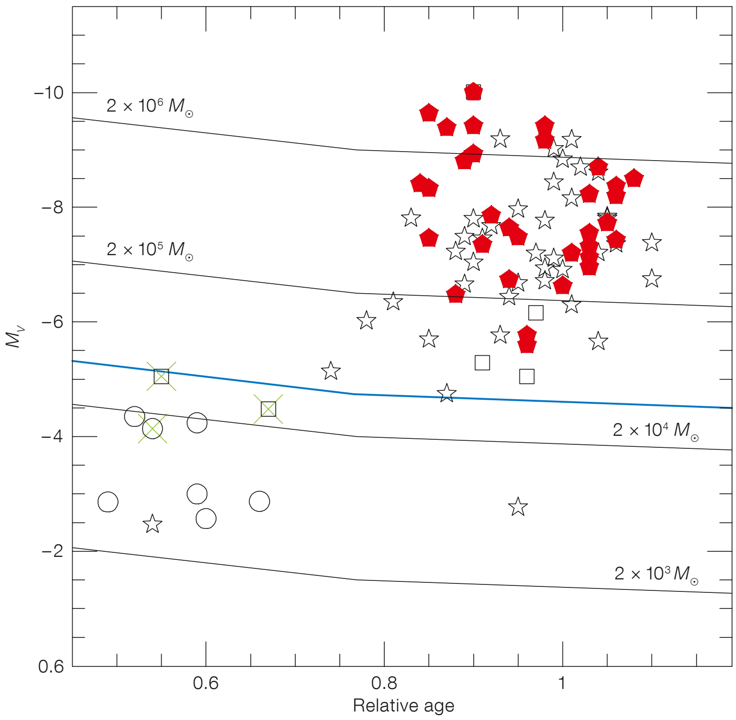

Figure 3. The relative age parameter is plotted *vs.* absolute magnitude M_V for globular and old open clusters. Red filled pentagons are for GCs where the Na–O anticorrelation has been observed. Open stars mark GCs for which insufficient data about the Na–O anticorrelation is available. Squares are for the clusters of the Sagittarius dSph galaxy and open circles are for old open clusters (see Carretta et al., 2010a). Green crosses mark those clusters where the Na–O anticorrelation has been searched for but not found. Superimposed are lines of constant mass (light solid lines, see Bellazzini et al., 2008). The heavy blue solid line (at a mass of $4 \times 10^4\ M_\odot$) is the proposed separation between globular and open clusters.

mean square dispersion. A by-product of our work is a new metallicity scale for GCs based on homogeneous abundances from high resolution UVES spectra (Carretta et al., 2009c). The homogeneity and good statistics also allowed the first distinction between the He-rich, SG and the He-poor FG populations at the red giant branch (RGB)-bump (Bragaglia et al., 2010a) to be made, as foreseen by models.

Our first extensive study of the chemical composition of M 54 in the nucleus of the disrupting Sagittarius dwarf galaxy showed a metallicity dispersion and Na–O anticorrelation in both the metal-rich and metal-poor component (Carretta et al., 2010b), with similarities with Omega Centauri, probably indicative of a similar origin in dwarf spheroidal galaxies.

The Li abundances offered a complementary approach. Li is easily destroyed in stellar interiors so, if there is no Li production within the polluters, Li and O should be positively correlated and Li and Na anticorrelated. Measures of O, Na, and Li abundances in the same stars are rare, but D'Orazi and Marino (2010) found no Li–O correlation in a sample of about 100 giants in M4. If confirmed in other GCs, this would be explained only with Li production in the polluters, very likely intermediate-mass AGB stars.

Finally, we found that the fraction of Ba-stars (which arise from mass transfer in binaries) is higher among FG stars (D'Orazi et al., 2010). This prompted us to estimate the binary fraction from multi-epoch measurements of radial velocities, available for three of our GCs, finding that the binary fraction of SG stars is much lower than that of FG stars. Binaries are more common in low than in high density environments: our finding is then a direct probe of the ambient condition at the distant epochs where the bulk of different stellar generations formed in GCs.

These results are unprecedented and were made possible by the large samples of high resolution spectra available, and by the high degree of homogeneity attained by the analysis procedures adopted in our survey.

Future directions

Our results, as well as the discovery of multiple MSs from high precision Hubble Space Telescope photometry, are opening unexpected and fascinating windows on the quest for the formation and evolution of massive stellar clusters. However, several issues remain presently unsolved, like the nature of the polluters, the overall timescale of the self-enrichment, the existence of material with pristine composition diluting the products of the polluters, the relation between the formation of GCs and that of the Galactic Halo, the role of different populations on the dynamical evolution of GCs, the connection between multiple populations and other properties of GCs (e.g., mass, the second parameter on the HB, or the blue and red sequences of GCs seen in many galaxies), and the relation between GCs and the nuclei of dwarf galaxies, and many more.

With its large set of very competitive instruments, the VLT is likely to play a fundamental role in this game even in the future. UVES and FLAMES observations were essential in revolutionising our view of the GCs. New perspectives are possible with the high sensitivity of X-shooter, revealing the spectra of faint MS stars (see Bragaglia et al., 2010b), or the access to near-infrared spectra provided by CRIRES.

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