From Lithium to Uranium: Elemental Tracers of Early Cosmic Evolution
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Observations of globular clusters with FLAMES

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Abstract. We present preliminary results of a few observing programs conducted with the FLAMES fiber facility at VLT2 ESO telescope. These programs show the large potentiality of FLAMES for investigations of globular clusters. The programs described here concern the derivation of precise reddening and metallicity for globular clusters, and the derivation of abundances for stars on the main sequence of ω Cen. Reddenings with errors of $\Delta E(B-V) = 0.005$ mag and metallicities with errors of ± 0.02 dex (in a scale defined by local subdwarfs) can be obtained in very short observing time. Our results for ω Cen show that the blue main sequence is more metal-rich than the red-main sequence: this requires a large He-content for the blue main sequence.

Keywords. Galaxy: globular clusters: individual (NGC6752, ω Cen), stars: abundances, instrumentation: spectrographs

1. Introduction

Progresses in instrumentation often lead to new unexpected discoveries, as well as to significant advances in our understanding of astronomical phenomena. The advent of efficient high dispersion spectrographs at the focuses of large (8-10 m class) telescopes similarly marked a new view on the formation and evolution of globular clusters (GCs). For a long time, GCs were considered the observational templates of simple stellar populations, and as such they greatly contributed to our understanding of stellar evolution. Most GCs presents well defined sequences in their colour-magnitude diagrams, that can only be explained by a high degree of homogeneity in their heavy element content, as well as to a narrow range of ages for their stars. Admittedly, there were some disturbing facts, mainly related to the distribution of stars along the horizontal branch (HB), a magnifier of whatever small star-to-star variations exist in age, chemical composition, and mass loss within a GC. However, most authors simply considered these disturbing facts as noise factors, only relevant to specialist of the field. In this context, it was assumed that GCs formed in a single gigantic episode of star formation, with no resolution in time, and then evolved passively, the only significant episodes at later phases being due to the dynamical evolution of a huge number of point-like mass particles.

However, mainly thanks to the impact of the observations gathered using UVES at ESO VLT2, our view of GCs is now changing. We are discovering that they are not the simple objects we thought of. The formation of their stars seem to have occurred in several episodes, which all likely happened within a few hundreds of millions of years, below the resolution possible with current photometric techniques. While in general not disturbing the abundance pattern for the heaviest elements (with a few, very significant exceptions, see Section 3), nonetheless these different episodes left clear footprints on the chemical composition of the GC stars: the GCs do have their own chemical evolution history different from what we can see in the field. In fact, while in this last case we always observe the combined effects of a large variety of polluters, chemical enrichment in GCs is characterized by the selective contribution of only very restricted groups of stars - in some resemblance with the case of mass-exchange binaries. This gives raise to extraordinary abundance patterns, that should be careful taken into consideration when considering GCs as e.g. distance indicators. Furthermore, it offers unique opportunities to study the contribution to chemical enrichment of a few peculiar groups of stars, like (perhaps) the less massive stars exploding as core collapse SNe, or the heaviest ones experiencing thermal pulses. In this respect, GCs are very useful counterparts of extremely metal-poor stars, where also we look for the signatures of pollution from restricted groups of peculiar stars.

This revolution in our ideas about GCs is just beginning: the same existence of self-enrichment processes has only recently become widely accepted, and we are still far from a coherent picture. Extensive observations of large samples of GC stars may disclose new possibilities for our understanding of these processes, as well as their relation to old still unsolved issues like the second parameter effect. Determining the composition of GC star-by-star is a very lengthy procedure, even for 8-10 m class telescopes. However, the new fiber facility FLAMES available at ESO VLT2 since 2003 (Pasquini *et al.* 2002) allows a two orders of magnitude step forward in this area, and it is beginning to revolutionize the field. FLAMES is composed of four different components: a field correcting lens, the Australian-made Oz-Poz fiber positioner, and fiber links to two spectrographs: UVES, allowing moderately high resolution, $R \sim 45000$, and large spectral coverage with a maximum of 8 fibers; and GIRAFFE, where a maximum of 132 spectra at resolution $6000 < R < 30000$ can be obtained simultaneously in the MEDUSA mode (there is an additional integral field mode called ARGUS, whose results will not however be described here).

Our group, including astronomers in Padua and Bologna, is using FLAMES for a number of projects concerning GCs. In this contribution we will describe the final results obtained in one of these programs, as well as preliminary data for another project; preliminary results for a third one are described in the poster contribution by Carretta *et al.* at this meeting. While these results are only preliminary, they dramatically show the impact of the order of magnitude progresses possible with FLAMES in GC science.

2. Accurate Reddenings and Metallicities for Globular Clusters

Determination of accurate ages for GCs is fundamental in various astronomical areas. Accurate estimates of the absolute ages of (the oldest) GCs may provide a stringent lower limit to the age of the Universe and constrains the exponent of the equation of state of the dark energy, independently of type Ia SN observations (see e.g. Gratton *et al.* 2003). Furthermore, within the framework of a standard ΛCDM model, where the age of the Universe is accurately fixed at 13.7 ± 0.2 Gyr by the WMAP results (Spergel *et al.* 2003), the age of GCs can be used to constrain the epoch of formation of the Galaxy, linking the local Universe to the distant one (see Carretta *et al.* 2000; and Gratton *et al.* 2003). Relative ages are fundamental to describe the early history of our Galaxy. In this framework it should be noted that galactic GCs divide into two main groups: halo and thick disk (or bulge) GCs (Zinn 1985). The differential age method suggests that these two groups might have ages different by about 2 Gyr (Rosenberg *et al.* 1999). This has implications for both cosmology (where only the oldest GCs are of interest) and galactic evolution. Observations of GC systems in other galaxies suggest a link between GC formation and strong dynamical interactions (Peebles & Dicke 1968; Schweizer & Seitzer 1993). The oldest group of GCs might then be related to the very early phases of the galactic collapse, while the second one may instead trace a later accretion event (see Freeman & Bland-Hawthorn, 2002), possibly related to the end of the thick disk phase indicated by chemistry (Gratton *et al.* 1996, Gratton *et al.* 2000; Fuhrmann 1998).

An important goal is then to derive absolute ages with internal errors of ±1 Gyr for a wide sample of GCs. Ages for GCs with such small errors may be derived only using the luminosity of the turn-off (TO): this on turn requires accurate distances, with errors $< 5\%$. In perspective, most accurate and robust distances (error $< 2\%$) for a few GCs will be obtained using geometrical methods (Piotto *et al* 2004), an area where also FLAMES plays a crucial role (allowing fast determination of radial velocities for a wide number of stars). However, at present, distances with errors of 3-5% can be obtained for a larger sample of GCs using the Main Sequence Fitting Method (MSFM), exploiting local subdwarfs as standard candles (see Gratton *et al.* 1997; Pont *et al.* 1998; Carretta *et al.* 2000; Gratton *et al.* 2003). Main sources of errors in MSFM are possible systematic differences in reddenings and metallicities between field and GC stars. Both of them can be reduced to within the required accuracy if a reddening-free temperature indicator is used for both field and GC stars of similar evolutionary phases: the analysis of the results of the ESO LP 165.L-0263 (Gratton *et al.* 2003) showed that this approach may provide reddenings accurate to $\Delta(B-V) = \pm 0.005$ mag, metallicities accurate to ±0.04 dex, distances accurate to 4%, and ages with errors of about ±1 Gyr. Also geometrical distances (which determines the true distance modulus toward a cluster) will take advantage from accurate reddening and metallicity determinations, since apparent distance moduli are required to derive ages. Note that here we are only interested in relative reddening and metallicity determinations: the adopted scale may be tied to that of field stars for which analogous observations can be made.

To show feasibility of this approach, we performed a pilot program on NGC6752 using FLAMES (Gratton *et al.* 2005). Accurate reddenings for GCs could be obtained by comparing the colour-temperature obtained using temperatures from $H\alpha$, with that given by standard colour-temperature calibrations. The main difficulty in such derivations is the large errors in temperatures due to uncertainties on the removal of instrumental signature for each individual stars. The large number of spectra that could be obtained using GIRAFFE allowed a proper reduction of this source of errors. On the other side, low resolution and S/N were not too critical in such observations, allowing to use faint turn-off stars. The simultaneous acquisition of spectra of a few red giants with UVES allowed additionally an accurate determination of the chemical composition. For this purpose we preferred to use relatively warm stars, for which the analysis is expected to be robust. The large multiplexing opportunity offered by FLAMES at VLT2 allowed us to obtain spectra centred on $H\alpha$ at a resolution of R=6000 and $5 < S/N < 50$ for 120 stars near the turn-off of NGC6752 with GIRAFFE from a single 1300 seconds exposure. This set of spectra was used to derive effective temperatures from fittings of $H\alpha$ profiles with typical errors of about ±200 K and reddening estimates with individual errors of 0.05 mag. Averaging all individual reddenings, a high precision reddening estimate has been obtained for the cluster: $E(B-V) = 0.046 \pm 0.005$. The same exposure provided UVES spectra of seven red giants near the bump at a resolution of 40,000, and $20 < S/N < 40$. These spectra, combined with temperatures from colours (corrected for our high precision

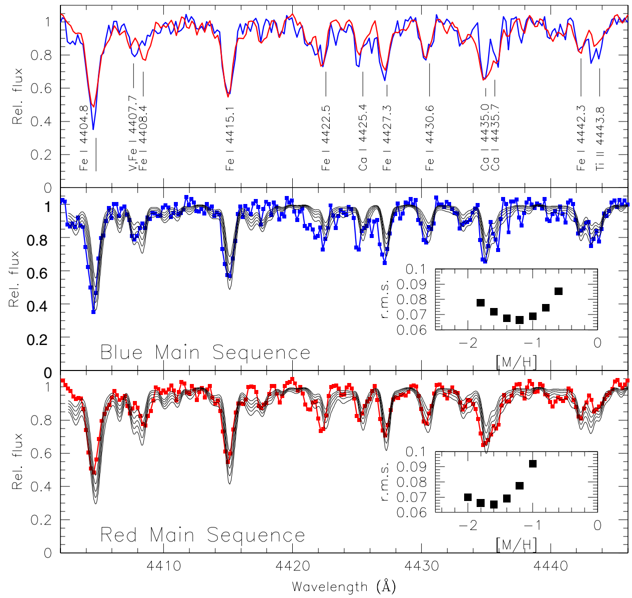

Figure 1. The average bMS (blue line) and rMS (red line) spectra are overplotted in the upper panel, where a few relevant spectral lines are also indicated. Though a few lines (e.g. Fe I 4404.8, Ti II 4443.8) are clearly different in the two spectra, the effect on the line strength due to the difference in metal content between the bMS and rMS stars is partially compensated by the temperature difference. The average bMS (middle panel) and the average rMS (lower panel) spectra are compared with synthetic spectra for different metallicities ([M/H] = −1.6, −1.4, −1.2, and −1.0 for the bMS; [M/H] = −2.0, −1.8, −1.6, −1.4, and −1.2 for the rMS). In these two last panels, observed spectra are represented by colored lines and dots; synthetic spectra are the thin solid lines.

reddening value) provided Fe abundances with internal errors of 0.026 dex, and with average metallicity [Fe/H]=$-1.48 \pm 0.01 \pm 0.06$ dex (random + systematic). Abundances were obtained for several other elements, allowing e.g. an accurate estimate of the ratio between the $\alpha-$elements and Fe ([α/Fe]=$+0.27 \pm 0.01$). The O-Na anticorrelation is evident from our UVES data, in agreement with past results.

The success of this procedure shows the extreme power of FLAMES for analysis of GCs: these accurate reddenings and metal abundances, combined with distance determinations from cluster dynamics or main sequence fitting, and with high quality colour-magnitude diagrams, could allow derivation of ages with unprecedented errors below 1 Gyr for individual GCs.

3. The Main Sequence of ω Centauri

Omega Centauri is the GC with the most complex stellar population: understanding its star-formation history might give fundamental information on the star-formation processes in more complex systems such as galaxies. A recent and puzzling result is the identification of a double main sequence (DMS)originally discovered by Anderson (1997), and discussed in detail by Bedin *et al.* (2004, B04). ω Cen is the only GC to show two MS populations. Based on investigations of the stars on the RGB, we would expect a MS mainly populated on the blue edge, corresponding to the dominant metal-poor population ([Fe/H]< -1.6). However, the bluer MS (bMS) is much less populous than the red MS (rMS), containing only $\sim 25\%$ of the stars. B04 discussed a number of possible explanations: that the bMS could represent (i) a super-metal-poor ([Fe/H]< -2.0) population, or (ii) a super-helium-rich (Y$>$ 0.3) population (see also Norris 2004), or, finally, (iii) a background object, 12 kpc beyond ω Cen.

We observed ω Cen with FLAMES@VLT+GIRAFFE. We used the MEDUSA mode, which allows obtaining 130 spectra simultaneously. We used the low-resolution mode LR2, which gives R = 6400 in the 3960 − 4560 Å range. Twelve one-hour spectra were obtained for each of 17 rMS stars and 17 bMS stars (in the magnitude range $20 < V < 21$). The spectra were shifted and co-added in order to obtain one single bMS and a single rMS spectrum, for a total of 204 hours of exposure time per spectrum, and an average $S/N \sim 30$.

The effective temperatures that we used are the average of the values derived from the star colors and from the profiles of Hα. The final adopted temperatures are 5200 K for the rMS, and 5400 K for the bMS. Uncertainties in these temperatures are $\pm$100 K, but the difference is better determined. Metal abundances (mainly Fe) were obtained by comparing the observed average spectra for the bMS and the rMS with synthetic spectra computed with different metal abundances over the region 4405 − 4445 Å. Our best values are those that minimize the r.m.s. scatter of the residuals between the observed and synthetic spectra. The results are shown in Fig. 1; the best values are [M/H]=-1.57 for the rMS, and [M/H]=-1.26 for the bMS. Internal errors of $\pm$0.1 dex in these abundances were estimated by comparing the values obtained from each half of the wavelength range separately. Systematic errors are dominated by uncertainties in the adopted temperatures: a change of 100 K in the effective temperatures causes a change of $\pm$0.2 dex in the derived abundances. Fig. 1 clearly shows that the bMS stars are more metal rich than the rMS ones by 0.3 ± 0.2 dex. This definitely removes the possibility raised in B04 that the bMS represents a super-metal-poor population. The [Fe/H] of the rMS is consistent with the peak of the abundance distribution of red giants in ω Cen (Suntzeff & Kraft 1996; Norris *et al.* 1996), while the bMS corresponds roughly to the second peak in the distribution obtained by those authors. Also, the relative number of stars in the two sequences is consistent with the relative numbers in the RGB.

Our spectra also shows that the bMS and rMS have the same radial velocity, making the already remote possibility that the bMS represents a background object even more unlikely. Additionally, preliminary results by Anderson & King (2005, in preparation) show that the average proper motions of the two populations are undistinguishable. In summary, all observational evidence indicates that the bMS stars are ω Cen members. Still, we remain with the puzzling observational result that the bMS stars are more metal rich than the rMS ones. The only remaining explanation is that the bMS have a strong He enhancement. The ridge line of the bMS is best fitted by an isochrone for $Y = 0.38$.

Where does the He of the abnormal bMS of ω Cen come from? Most authors try to explain the abundance spread within ω Cen as a peculiar chemical evolution history for this object, which possibly was once the nucleus of a dwarf galaxy (for a comprehensive discussion of the literature, see Gratton *et al.* 2004). In this framework, the enormous production of He is attributed to pollution by the ejecta of a well-defined group of stars. If we compare the bMS and rMS abundances, the difference of helium abundance required to explain our data is about $\Delta Y = 0.14$, while the analogous variation in heavy metal content is $\Delta Z < 0.002$ (assuming that the variation of abundances of the Fe-peak elements is representative of all metals). The $\Delta Y/\Delta Z > 70$ suggested by these data is more than an order of magnitude larger than the value found appropriate for Galactic chemical evolution (see, e.g., Jimenez *et al.* 2003). We are forced to look for stars which produce He very efficiently. The first obvious candidates are intermediate-mass stars, which according to various authors (see, e.g., Izzard *et al.* 2004) may indeed produce large amounts of He, which can pollute the surrounding nebula during the AGB phase. However, the amount of ejected He does not seem to be enough to raise Y to the values needed to explain the bMS. Moreover, these same stars should also produce C efficiently; the fact that we found a similar C abundance for both the rMS and bMS stars seems to exclude this possibility. Norris (2004) suggested that massive stars can be the source of the high He content. However, while it is conceivable that heavier elements collapse into the central black hole, we do expect that a large amount of ejected He would be accompanied by a corresponding large amount of CNO and other α-elements. This fact seems to be contradicted by the observational evidence. An appealing alternative may be represented by the smallest among core-collapse supernovae (SNe). According to the prescriptions by Thielemann *et al.* (1996), complemented by data by Argast *et al.* (2002), SNe with initial masses smaller than about $10 - 14\ M\odot$ produce significant amounts of He, while producing only small amounts of heavier elements.

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