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Understanding the horizontal branch of globular clusters using FLAMES

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Abstract. An adequate understanding of the horizontal branch (HB) of globular clusters is still one of basic issues of stellar evolution. Several parameters likely influence the location of stars along the HB, the most important being metallicity and age. However additional factors are important. Fundamental progress has been done in the last few years since it was acknowledged that globular clusters host multiple stellar populations. We present the results of new spectroscopic surveys of stars on the HB of globular clusters conducted with FLAMES at VLT that show how the distribution of stars along the HB is strongly influenced by the multiple population phenomenon. New perspectives are then discussed.

Key words. Stars: abundances – Stars: evolution – Stars: Population II – Galaxy: globular clusters

1. Introduction

Evidence for multiple stellar populations in globular clusters (GCs) come from both spectroscopy and photometry. Abundance anomalies among stars in GCs were known from the early '70s but for a long time they were attributed to peculiar evolution (Kraft 1994). However, Briley et al. (1997) and Gratton et al. (2001) (this last work done using the freshly commissioned UVES at VLT-UT2) discovered that these abundance anomalies extend to main sequence stars and are then primordial effects. Stars of a second generation (SG) were born from the ejecta of a fraction of the stars of an earlier one. The SG stars show a characteristic abundance pattern, with enhancement of the elements produced by H-burning at high temperature (Denisenkov & Denisenkova 1989). The most typical features are the anti-correlations existing between various pairs of elements (C-N, O-Na, Mg-Al). Those concerning the heavier elements, known since the early '90s from the work by the Lick-Texas group, were extensively used by Carretta et al. (2009a) and Carretta et al. (2009b) to provide a comprehensive picture of the phenomenon in a survey of the chemical composition of red giants in GCs made with FLAMES at VLT-UT2. As discussed in Carretta et al. (2010), the anti-correlation pattern is present in all *bona fide* GCs; the SG stars are usually the majority of stars in GCs; whenever adequate data exist and cluster relaxation time is

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long enough, they are more centrally concentrated than first generation one; and there is a strong correlation between the extension of the anti-correlation and the absolute magnitude of the cluster. However, at variance with galactic chemical evolution, only a few classes of stars contributed to the chemical enrichment in GCs, likely because their potential wells are shallow. Which were these stars is still not clear, the two most popular candidates being fast rotating massive stars during their main sequence phase (Decressin et al. 2007) and massive AGB stars undergoing hot bottom burning (Ventura et al. 2001). A common feature of these polluters is that Na-rich/O-poor stars might have large He content.

Evidence of multiple populations from photometry dates back even earlier than that from spectroscopy, from at least the mid '60s, when it was discovered that at least a second parameter (other than metallicity) is required to explain the colours of stars along the horizontal branch (HB) of GCs (see later) and that there is a huge spread in colours among the red giants of the largest Milky Way GC, ω Cen. The latter was readily interpreted as a spread in metal abundance, that is a clear sign of multiple stellar populations. However, the great relevance of these facts was not properly understood until exquisite photometry with HST allowed Bedin et al. (2004) and Piotto et al. (2007) to show that the main sequence of ω Cen and NGC 2808 (the latter is a GC where all stars share the same overall metal abundance) are split in various sequences. In both cases, it could be shown that the only logical explanation of the split is that in these GCs there are various stellar populations with very different He abundance. In the case of ω Cen, this demonstration required acquisition of good blue spectra ($S/N \sim 100$ and resolution $R \sim 6000$) of 21st magnitude main sequence stars: this was achieved by Piotto et al. (2005) by summing up spectra of about twenty stars in both sequences, simultaneously observed for 12 hrs with FLAMES at VLT, yielding an effective exposure time of 240 hrs on both sequences! The most He-rich population of ω Cen and NGC 2808 have a spectacular He content of $Y \sim 0.38$ which is not matched even by the most metal-rich field population in galaxies. This clearly indicates peculiar nucleosynthesis. Further work with both HST and ground-based photometry showed that multiple populations may be traced not only on the main sequence, but also on the subgiant branch and red giant branch (Piotto 2009). With suitable choices of the bands (e.g. using Strömgren photometry), virtually all GCs explored show multiple sequences. When accurate enough data are available, even photometry alone allows to infer many details of the chemical composition of the different populations as shown by the analysis of 47 Tuc by Milone et al. (2012).

2. Multiple populations and the horizontal branches

The concept of multiple stellar populations has revolutionized our understanding of GCs. It has a number of broad implications, including e.g. the role of GCs in the assembly of galaxies. In this talk, we will focus on its impact on the explanation of the long standing issue of the so-called second-parameter.

Sandage & Wallerstein (1960) found that there is a correlation between the colours (i.e. temperatures) of stars along the HBs of GCs and metallicity. However, shortly after Sandage & Wildey (1967) and van den Bergh (1967) found that GCs of similar metallicity may have very different HBs. This issue has been since called the second-parameter problem and its explanation has defied astronomers. For a long time it was suspected that variations in age play a role (Lee et al. 1994). However, derivation of accurate ages for GCs requires precise distances, and insofar distances were based on assumptions about the absolute magnitudes of HB stars, there was a strong risk of circularity. Only quite recently, accurate photometry for main sequence stars disclosed the possibility to derive distances for GCs that were not dependent on HB stars. Using such distances, Dotter et al. (2010) found that the median colours of stars along the HB can be explained quite well by the combination of age and metallicity, if a suitable - metal dependent - total mass loss is assumed for GC stars. There is still some residual scatter in the relation, that they found to be correlated with cluster concentration. However, Dotter et al. analysis is still based on the idea that GC are single stellar populations; likely for this reason, they could not explain other features clearly related to the second-parameter issue, in particular the huge spread in colours along the HB found in some GCs. This had already found to be correlated to cluster luminosity by Recio Blanco et al. (2006).

In a paper in 2010 we reconsidered this issue within the multiple population context. D'Antona & Caloi (2004) had already shown that the distribution in colours of stars along the HB of NGC 2808 can be explained by variations in their mass, on turn due to variations in the He content, because the main sequence evolution of He-rich stars is faster than that of He-normal stars. If the two groups of stars lose mass at a similar rate when on the red giant branch, He-rich stars are expected to be less massive and then bluer when on HB - note that the same argument was made in the '70s by Norris et al. (1981) for other GCs. While D'Antona and co-workers examined a few other GCs in the same perspective, we decided to took a more extensive approach and examined the whole sample of clusters in the Piotto et al. (2002) HST snapshot and Rosenberg et al. (1999) ground based surveys. Our analysis indicated that the morphology of the HB of GCs may be well explained by a combination of three parameters: metallicity, age, and variations in the He abundances, themselves related to the cluster luminosity, likely a proxy for the cluster mass, once a simple universal mass loss, linearly dependent on metallicity, is adopted. This does not exclude that a few HB stars may have anomalous colours due e.g. to evolution in binary systems, but this is likely only a minor effect.

3. Abundances for horizontal branch stars

While very suggestive, this picture requires some direct confirmation. Since we need spectroscopy of rather large sample of stars, UVES and FLAMES at VLT are extremely competitive instruments. Ideally, we should derive the abundance of He for stars in different location along the HB. Unfortunately, this is not easy for various reasons. Photospheric He lines are vanishingly weak in stars cooler than ~ 8500 K. In addition, the atmospheres of HB stars with temperature $> 11,500$ K are in radiative equilibrium: photospheric abundances for these stars do not reflect their original values, but are rather determined by the effect of gravitational sedimentation and radiation pressure (Behr et al. 1999). The He test then works only over a very limited range of temperatures along the HB, and even in this case, very high quality spectra are required to achieve the accuracy needed to separate He-rich and He-poor stars.

However, the abundances of Na and O are expected to be correlated with those of He and their variations are much larger. Strong features of Na and O are easily observable over the whole range of temperatures below 11,500 K. Hence, with some limitations (the original composition of the warmer stars cannot be determined), Na and O abundances can be used for much more extensive tests than He. Using UVES spectra, Villanova et al. (2009) determined Na and O abundances in five stars of NGC 6752, a cluster with an extremely blue HB, so that only the cooler HB stars have temperatures $> 11,500$ K. We then expected that these stars should be O-rich and Na-poor, unless they are in a late evolutionary phase, in which case they are over-luminous, and most likely O-poor and Na-rich. This was exactly what Villanova et al. found: four less luminous and then likely zero age HB stars - showed up to be O-rich and Na-poor, while the fifth stars, which is overluminous, is O-poor and Na-rich.

After this first success, observations were extended to other clusters. Marino et al. (2011) used UVES at VLT-UT2 to determine the abundances of a few stars on both sides of the instability strip of M 4, the closest GC. They found that, as expected, red HB stars are O-rich and Na-poor, while blue ones are O-poor and Na-rich. Villanova et al. (2012) used the same spectra to derive the He abundance in the warmer stars; these stars appear more He-

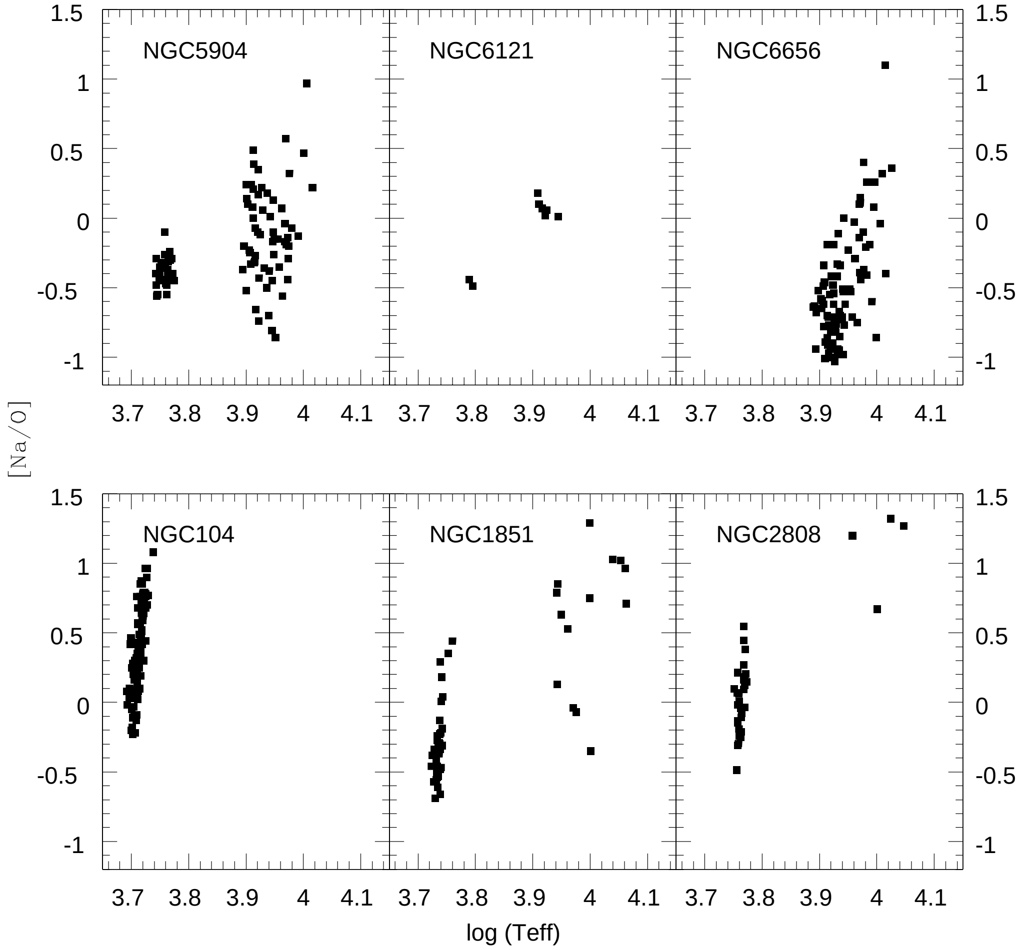

Fig. 1. Run of the [Na/O] ratio with effective temperature among HB stars in six GCs. Data are from Marino et al. (2011), Gratton et al. (2011), Gratton et al. (2012a), and Gratton et al. (2012c). Note that these clusters have very different HB morphology and that only a fraction of the HB has been sampled in these studies: RR Lyrae variables (HB stars in the temperature range 3.78< $\log T_{\rm eff}$ <3.90) and stars warmer than 11,500 K ($\log T_{\rm eff}$ > 4.06) were excluded because derivation of their original composition is more difficult or even impossible from the usual abundance analysis.

rich than those of similar colours in NGC 6752, again in agreement with expectations.

In the last year we undertook a more extensive spectroscopic survey of HB stars in various GCs using FLAMES at VLT-UT2, in order to further confirm this scenario. We selected GCs covering a wide range of HB morphologies, all with a quite rich population of stars cooler than 11,500 K. Results for the first four clusters (47 Tuc, NGC 1851, NGC 2808, and M 5) have already been published in (Gratton et al. 2011), (Gratton et al. 2012a), and (Gratton et al. 2012c). Data for M 22 are in an advanced stage of analysis. In each cluster we observed with Giraffe ∼ 100 blue and red HB stars, avoiding variables. To save precious telescope time, two Giraffe gratings were considered (HR12 and HR19) allowing to measure the OI triplet and the Na D lines, which are the only features of O and Na detectable over the whole relevant range of temperature. Other lines of N, Na, Mg, Si, Ca, Ti, V, Mn, Fe, Ni, and Ba, as well as of CN, may be seen in these spectra, mostly in the case of red HB stars. Determination of consistent abundances over the wide range of temperatures covered by these stars is not easy and care should be taken to obtain the most accurate atmospheric parameters and to properly take into account departures from LTE in the line formation. Once these effects are taken into consideration, abundances for red HB stars compare very well with those obtained for red giants, while uncertainties are larger for blue HB ones. The picture emerging from all this data (see Figure 1) is quite clear, well confirming the hypothesis that the distribution of colours of stars along the HB of each cluster is mainly determined by variations in the He content. We found a good correlation between the Na/O abundance ratio and colours in NGC 2808, 47 Tuc, and M 22. The case of NGC 1851 is complex, with two separate correlations between Na/O abundance ratio and colour for red and blue HB stars, in agreement with what found for the two subgiant branches of this cluster (Gratton et al. 2012b). Finally, while some correlation of abundances with colours is present for M 5, we found that in this cluster there should be some significant star-to-star variation in the mass loss in addition to variations in the He content. The case of M 5 might possibly be not unique, suggesting that in spite of the great successes of the multiple population scenario, we still have something to learn about the second-parameter issue.

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