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Multiple stellar populations in globular clusters

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Abstract. Spectroscopic and photometric studies have established that multiple populations of stars with different helium and light elements are ubiquitous in Galactic globular clusters (GCs). In addition, it has been recently discovered that about 18% of the studied GCs host internal variations in heavy elements. In contrast, the young and intermediate-age GCs of both Magellanic Clouds, which exhibit multiple sequences along the CMD, seem to be chemically homogeneous. In this paper, I will provide a short review of these intriguing topics by discussing the main properties of the stellar populations in old Galactic GCs and in the young clusters of the Large and Small Magellanic Cloud.

1. Introduction

The past decade has witnessed a major advancement in research on globular clusters (GCs). The evidence of multiple sequences along the color-magnitude diagrams (CMDs) of tens of ancient GCs as well as in young clusters of both Magellanic Clouds has been one of the main recent discoveries in the field of stellar populations.

Specifically, the synergy of spectroscopic and photometric studies has revealed that nearly all the Galactic GCs host distinct populations of stars with different abundance of helium and of some light elements involved in the CNO cycle, including C, N, O, Na, and Al (e.g. Carretta et al. 2009a; Piotto et al. 2015; Milone et al. 2017). Multiple populations have been identified along the entire mass interval spanned by present-day GC stars, from ∼0.8 solar masses to the H-burning limit.

While the majority of Galactic GCs has homogeneous abundance of heavy elements (e.g. Carretta et al. 2009b), a recently-discovered class of ‘anomalous’ GCs exhibits stellar populations with different abundance of iron, s-process elements, and overall C+N+O (e.g. Marino et. al. 2009; 2015; Yong et al. 2014; Johnson et al. 2017). Multiple sequences are not a peculiarity of the old Galactic GCs but are a common feature of young and intermediate star clusters in the Magellanic Clouds.

In this paper, I illustrate the observational scenario and summarize the main properties of multiple stellar populations (MPs) in the old Galactic GCs and in the young clusters of the Large and the Small Magellanic Cloud.

2. Multiple populations along the color-magnitude diagram

Photometric diagrams made with appropriate colors and magnitudes are powerful tools to investigate the multiple-population phenomenon among millions of GC stars at different evolutionary phases.

Thanks to such innovative photometric investigation, MPs have been identified and characterized along the entire CMD of GCs, from the tip of the red-giant branch (RGB) towards the H-burning limit. In the following, we take the nearest GC, NGC 6121 (M 4), as an example to illustrate typical features of MPs in GCs.

2.1. The red-giant branch and the upper main sequence

About fifty years ago, the early studies on MPs were mostly based on the CN and CH molecular bands in bright RGB stars. In the nineties, the investigation has been extended to a large sample of light elements, through high-resolution spectroscopy (see review by Kraft 1994).

The most-intriguing outcome of these studies was the evidence of internal star-to-star variations of several light elements like C, N, O, Na, and in some cases of Al, Mg, and Si. Such elements are characterized by well-defined patterns, including the C-N, O-Na, Mg-Al anticorrelations and the Na-N, Na-Al correlations, that have been named 'chemical anomalies' (see reviews by Gratton et al. 2004, 2012a).

As an example, we show in the left panel of Fig. 1 the sodium-oxygen anticorrelation of RGB stars in NGC 6121 obtained by Marino et al. (2008) from high-resolution UVES@VLT spectroscopy. This cluster hosts two main groups of stars: a first population with the same sodium and oxygen abundance as halo field stars with the same metallicity and a second population of stars enhanced in sodium and depleted in oxygen.

Marino et al. (2008) discovered that the RGB of NGC 6121 is split into two main sequences in the U vs. $U-B$ CMD[1]. Even more intriguingly, the groups of Na-rich (O-poor) and Na-poor (O-rich) stars identified spectroscopically populate the two distinct RGBs in the CMD (see Fig. 1). This result has provided the link between the multiple populations discovered along the CMD and the chemical anomalies studied spectroscopically.

Nowadays it is widely accepted that GCs exhibit complex CMDs, which are formed by two or more intertwined sequences and correspond to distinct stellar populations with different chemical composition. The combination of spectroscopy and photometry gave rise to the 'golden age' for the understanding of stellar populations and depicted a new picture of the GCs. As we will discuss in the next sections, the spectro-photometric surveys of GCs are providing a huge amont of information on the multiple-population phenomenon.

2.2. Towards the H-burning limit

The near infrared channel of the Wide Field Camera 3 on board of *HST* has opened a new, exciting window in the study of MPs. Indeed, deep images collected through its F110W and F160W filters have revealed distinct MSs of M dwarfs, thus allowing us to characterize, for the first time, the multiple-population phenomenon among very low-mass stars (Milone et al. 2012a). The evidence that distinct populations are also present in fully-convective MS stars strongly supports the idea that they have a primordial origin.

The MS split is mostly due to the different oxygen abundance of 1G and 2G that affect the F110W and F160W flux of stars fainter than the MS kink through the strength of the H_2O molecule. An example, we reproduce in the right panel of Fig. 1 the NIR CMD of NGC 6121 from Milone et al. (2014), where the two distinct sequences of stars can be traced towards the H-burning limit.

Intriguingly, in the two studied cases of NGC 6121 and NGC 2808, the fraction and the relative oxygen abundance of 1G and 2G stars inferred from the M dwarfs are similar to the corresponding values derived from more-massive MS and RGB stars. These facts suggest that the stellar mass does not play a major role in determining the properties of the multiple populations.

[1] The $U-B$ vs. $B-I$ two-color diagram and the V against $U-B+I$ or $U-2B+I=C_{\mathrm{U,B,I}}$ diagrams are additional tools to identify MPs from ground-based Johnson photometry (Milone et al. 2012b, 2013; Monelli et al. 2013)

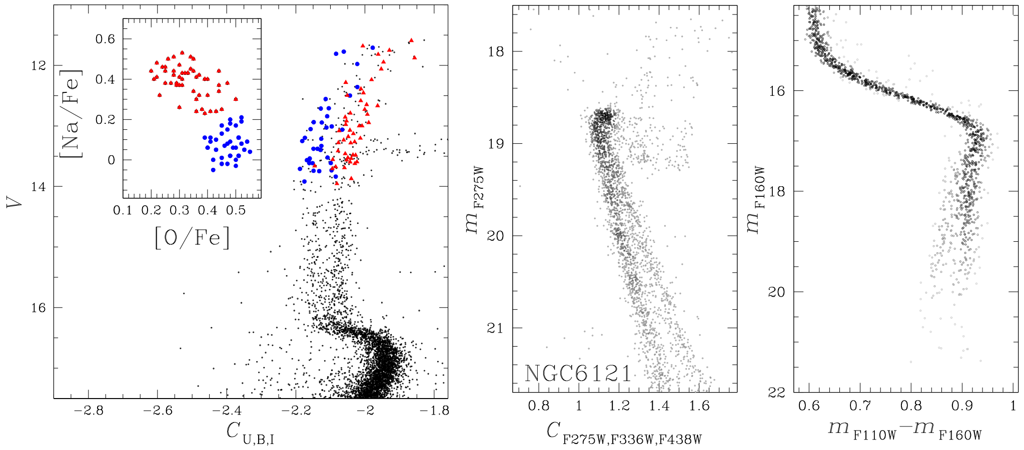

Fig. 1. This figure shows the distinct stellar populations of NGC 6121 through a variety of photometric and spectroscopic diagrams. The right-panel reproduces the V vs. $C_{\rm U,B,I}$ pseudo-CMD (Marino et al. 2017) derived from ground-based photometry (Stetson 2005), while the inset shows the Na-O anticorrelation of RGB stars (Marino et al. 2008). Middle panel plots the $m_{\rm F275W}$ vs. $C_{\rm F275W,F336W,F438W}$ diagram of RGB, SGB, and bright MS stars from *HST* (Piotto et al. 2015). The NIR CMD of stars at the bottom of the MS is shown in the right panel (Milone et al. 2014).

2.3. The horizontal branch and the second-parameter problem

The horizontal-branch (HB) morphology in star clusters is mostly driven by metallicy, which is considered the first parameter. Nevertheless, the presence of GCs with nearly the same [Fe/H] but different HB shapes, indicates that at least one second parameter is needed to reproduce the observations.

Since the sixties, the second-parameter problem of the HB morphology has been regarded as one of the main open issues of stellar astrophysics and many second-parameter candidates have been proposed (see Catelan 2009 for a review).

The overwhelming evidence for the existence of multiple stellar populations in GCs has provided a major step towards the understanding of the HB morphology. In this context, spectroscopic study of NGC 6121 has provided clear evidence of the connection between MPs and HB.

The HB of NGC 6121 is bimodal and well-populated on both sides of the RR Lyrae gap. The bimodality in Na and O, first observed among the RGB, is also present among the HB stars. Blue-HB stars belong to the second population and are O-poor and Na-rich, while red HB stars are first population (Marino et al. 2011, Villanova et al. 2012). Similar conclusions on several clusters have been provided by different authors (e.g. Milone et al. 2012a; Gratton et al. 2011, 2012b, 2013; Lovisi et al. 2012; Marino et al. 2013, 2014a).

The connection between HB morphology and MPs is consistent with the fact that 2G stars are enhanced in helium with respect to the 1G, which have primordial Y$\sim$0.25 as earlier suggested by D'Antona et al. 2002, 2005 and confirmed by direct spectroscopic measurement of He-rich stars along the HB (Marino et al. 2014b).

3. Properties of multiple populations in Galactic globular clusters

The *Hubble Space Telescope* UV Legacy Survey of Galactic GCs (Piotto et al. 2015) has provided high-precision multi-band photometry of MPs in a large sample of 57 GCs. This unique dataset has allowed us to build the first atlas of multiple MPs and derive their main properties.

We introduced the pseudo-two-colour diagram (or 'chromosome map'), built with a suitable combination of stellar magnitudes in the F275W, F336W, F438W, and F814W filters that maximizes the separation between MPs. In the chromosome map of most GCs (type-I clusters), stars separate in two distinct groups that we identify with the first (1G) and the second generation (2G). As shown in Fig. 2, we find that the properties of the sub-populations, including their number, the ratio between 1G and 2G stars and their distribution in the chromosome map dramatically change from one cluster to another.

The internal variation of helium and light elements correlates with cluster mass. The fraction of 1G stars ranges from ~8 per cent to ~67 per cent and anticorrelates with the cluster mass, indicating that incidence and complexity of the multiple population phenomenon both increase with cluster mass (Milone et al. 2017).

4. The anomalous globular clusters: a new class of Milky-Way satellites.

In past years, ω Centauri, which is the most-massive cluster of the Galaxy, was believed the only GC with variations in heavy elements (e.g. Norris & Da Costa 1995). Due to its mass and extreme chemical composition, this cluster is considered the remnant of a dwarf cannibalized by the Milky Way.

Nowadays it is well known that other clusters host two or more stellar populations with different iron and s-process elements, in close analogy with what has been observed in ω Centauri (e.g. Marino et al. 2009, 2012, 2015; Carretta et al. 2010; Yong et al. 2009, 2014; Johnson et al. 2015, 2017). Intriguingly, each group of metal-rich and metal-poor stars host sub-populations with different light-elements abundance (Marino et al. 2009). The sample of clusters that share these properties are called 'anomalous'.

Photometry has revealed that anomalous GCs exhibit distinctive chromosome map. Moreover, in contrast with the majority of GCs, they show a split SGB in purely optical CMDs with the fainter SGB joining into a red RGB which is populated by stars with enhanced heavy-element abundance.

From the study of 57 clusters, Milone et al. (2017) have concluded that the group of anomalous GCs is made of the 18% the analyzed clusters. Anomalous GCs include, among the others, NGC 6656 (M 22), NGC 1851 which is characterized by an extended stellar halo outside the tidal field (Olszewski et al. 2009; Marino et al. 2012), and NGC 6715 (M 54), which is the nuclear star cluster of the Sagittarius dwarf galaxy. The similarities with NGC 6715 makes suggest that anomalous GCs formed and evolved in an extra-galactic environment and are remnants of dwarf galaxies disrupted by the interaction with the Milky Way.

5. Young and intermediate-age clusters in the Magellanic Clouds

HST photometry has revealed that the CMDs of young (~30-800-Myr-old) clusters in the Large and Small Magellanic Cloud (LMC, SMC) exhibit either a broadened or split MS (e.g. Milone et al. 2013, 2016; Correnti et al. 2017; Li et al. 2017). Moreover, all clusters younger than ~ 2Gyr show an extended MS turn off (eMSTO, e.g. Bertelli et al. 2003; Mackey & Broby Nelsen 2007; Glatt et al. 2008; Milone et al. 2009). As an example of split MS and eMSTO, in Fig. 3 we provide the CMD of the ~200-Myr old cluster NGC 1866 and the ~1.4 Gyr-old cluster NGC 1846.

The split MS is consistent with two populations with different rotation rates: a red MS, which includes two third of the total number of MS stars and have rotational velocity close to the breakup value, and a blue MS, which is made of slow-rotating or non-rotating stars (D'Antona et al. 2015; Milone et al. 2016; Bastian et al. 2017). This conclusion is corroborated by the large number of Be stars (e.g. Keller et al. 1999; Correnti et al. 2017; Bastian et al. 2017) and by direct spectroscopic measurements of rotational velocity in MS stars (Dupree et al. 2017).

While the interpretation of the split MS is widely accepted, the physical reasons respon-

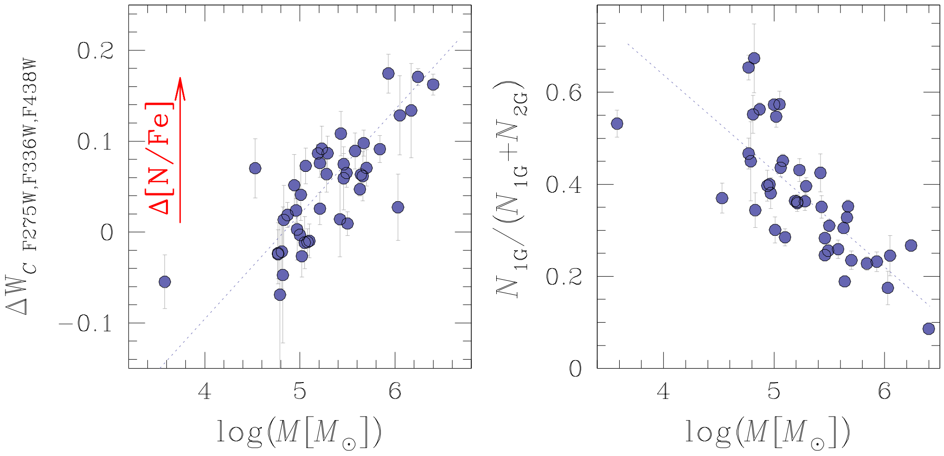

Fig. 2. *Left.* Correlation between the logarithm of the cluster mass and the RGB width, $\Delta W_{CF275W,F336W,F438W}$ which is a proxy for the maximum internal variation of helium and light elements. *Right.* Anticorrelation between the fraction of first-generation stars and the logarithm of the cluster mass (Milone et al. 2017).

sible for the eMSTO are still controversial. The most straightforward interpretation for the eMSTO is that young and intermediate-age clusters have experienced a prolonged star formation and host multiple generations with different age (Mackey et al. 2008; Goudfrooij et al. 2011).

According to these scenarios, the clusters with eMSTO could be the young counterparts of old GCs with multiple populations and provide the unique opportunity to constrain the MP phenomenon in young clusters (e.g. Keller et al. 2011; Conroy et al. 2011).

As an alternative, the eMSTO is another consequence of the presence of populations with different rotation rates (Bastian & de Mink 2009; Yang et al. 2011, 2013; Li et al. 2014; D'Antona et al. 2015) but it seems that stellar models with different rotation rates alone are not able to entirely reproduce the observations and some age spread is still required (e.g. Correnti et al. 2017; Goudfrooij et al. 2017).

D'Antona et al. (2017) have noticed that the blue MS of the studied young clusters host a sub-population of stars, which seems younger than the majority of blue-MS stars. They suggested that stars caught in the stage of braking from a rapidly-rotating configuration are responsible for this feature of the CMD, and that these stars behave now as a ∼30% younger stellar population.

6. Summary

In the last years, the knowledge of GCs has changed dramatically improved because of the overwhelming evidence for the existence of MPs. In this work I discussed the main properties of MPs as inferred from recent spectroscopic and photometric work. The main outcomes can be summarized as follows:

- Nearly all the old Galactic GCs host two distinct groups of 1G and 2G stars with different abundance of some light elements. Specifically, 2G stars are enhanced in He, N, Na and depleted in C and O with respect to 1G stars. Such chemical composition is rarely observed among field stars. MPs with different helium abundance populate different regions along the HB thus determining the HB morphology.
- The majority of GCs have homogeneous metallicity and constant abundance of light elements. A sub-class of GCs, which includes the ∼18% of the total number of studied clusters, host stellar populations

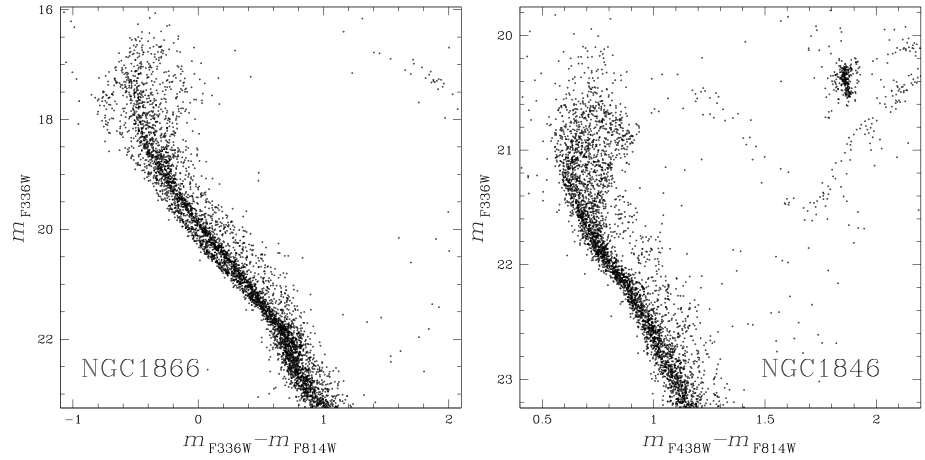

Fig. 3. CMDs of the LMC clusters NGC 1866 and NGC 1846.

with different content of iron and s-process elements. Such anomalous GCs are among the most massive Galactic GCs and, at least some of them, formed in extra-galactic environment.

– The properties of MPs, including the number of distinct populations, the relative fractions and their chemical composition dramatically varies from one cluster to another.
– The incidence and complexity of the multiple population phenomenon both increase with cluster mass. This is demonstrated by the evidence that the fraction of 2G stars with respect to the total number of cluster members and the maximum enrichment of helium and nitrogen both correlate with the cluster mass.
– All the studied young and intermediate-age star clusters in the LMC and SMC exhibit multiple MSs and eMSTO. It is not clear weather these multiple sequences are entirely due to stellar populations with different rotation rates or if they are also due to age variations. In this case, they could be the young counterparts of old GCs with MPs.

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