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Photometry of multiple populations in globular clusters

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Abstract. It is nowadays well established that almost all Galactic globular clusters host multiple stellar populations. Although various scenarios have been proposed, the formation and evolution of multiple populations is still matter of debate, and new observational inputs are needed. Thanks to the exquisite photometry extracted from recently collected HST UV data, we have been able to obtain a census of the multiple populations in one third of the Milky Way GCs, measure their frequency and their basic properties, including the chemical tagging of the different sequences. In this paper, I will present the results of this investigation and future prospects.

1. Introduction

Galactic globular clusters (GCs) are the most ancient stellar systems of the Milky Way, and for this reason they are a key element for understanding the mechanisms of formation and evolution not only of our Galaxy, but of all the galaxies for which we can not resolve the stars. It is nowadays well established that all the GCs so far studied host multiple stellar populations (MPs), characterized by stars having different chemical properties and belonging to different generations (Piotto et al. 2015).

As described in detail by Renzini et al. (2015), some observational fact arise from spectroscopic and photometric studies of MPs in GCs. Some of them are:

- **GCs specificity**: Stars of second-generation (2G) are observed mainly in GCs. No 2G stars have been observed in open clusters and only in few cases they have been observed among field stars;
- **Ubiquity**: the GCs analyzed so far (about 1/3 of all the Galactic GCs) host at least one 2G;
- **Variety**: each GC has its specific pattern of 2G stars and there are no two GCs that are alike;
- **Discreteness**: the color-magnitude diagrams (CMDs) of all the analyzed GCs show no continuous distribution of stars, but discrete sequences;
- **SN avoidance**: GC stars share almost the same [Fe/H] (with some few exceptions). It means that the matter out of which 2G stars formed was not contaminated by supernova products;
- **Hot CNO processing**: some observed chemical patterns (Na-O, Al-Mg, C-N anti-correlations) suggest that the material out of which 2G stars formed was processed by first-generation (1G) stars through CNO cycle and p-capture processes at high temperatures;
- **He enrichment**: 2G stars are also helium enhanced.

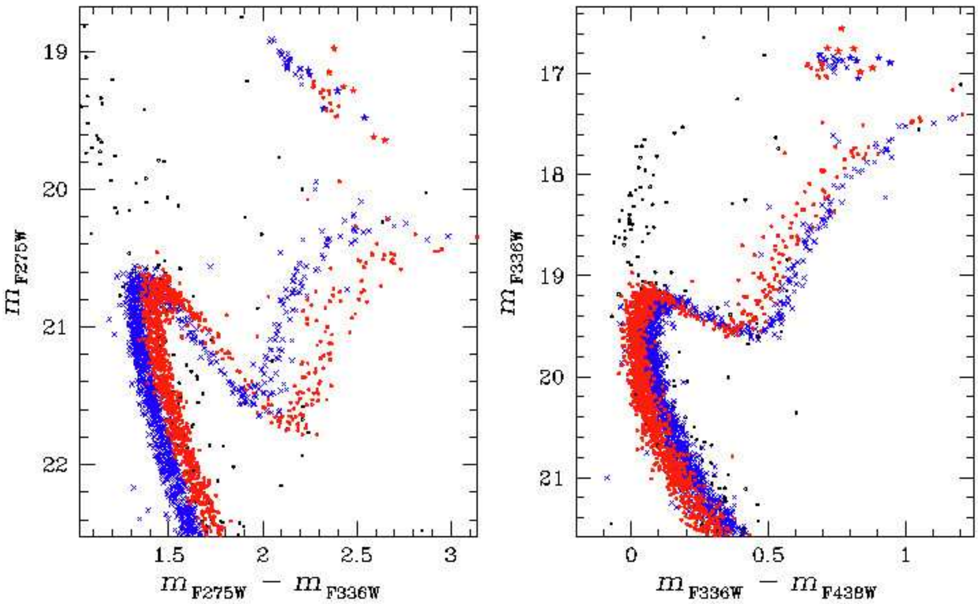

Fig. 1. The m_{F275W} versus $m_{\mathrm{F275W}} - m_{\mathrm{F336W}}$ (left-hand panel) and m_{F336W} versus $m_{\mathrm{F336W}} - m_{\mathrm{F438W}}$ CMDs of NGC 6352. In the first CMD, 1G stars (red dots) are redder than 2G stars (blue crosses), while in the second CMD, 1G stars have, on average, bluer colors than 2G stars (from Nardiello et al. 2015).

Thanks the exquisite photometry obtained during the Hubble Space Telescope (HST) UV Legacy Treasury project (GO-12311, GO-12605, GO-13297; PI: Piotto), we are able to identify and analyze the different populations hosted by each of the 57 GCs so far studied. In this paper, I will briefly outline the results obtained during this project, and the future prospects.

2. Photometry of MPs

The HST UV Legacy Treasury Project (Piotto et al. 2015) is a project based on the data of 57 GCs observed with HST in five filters: F275W, F336W, and F438W data were collected during GO-12311, GO12605, and GO-13297 missions (PI: Piotto); F606W and F814W observations were obtained during the GO-10775 (PI: Sarajedini). The UV photometry is a good tool for separating MPs in the CMDs of GCs. The reason why F275W, F336W, and F438W filters work so well is simple: these three filters include the molecular bands of OH (F275W), NH (F336W), CN and CH (F438W). For this

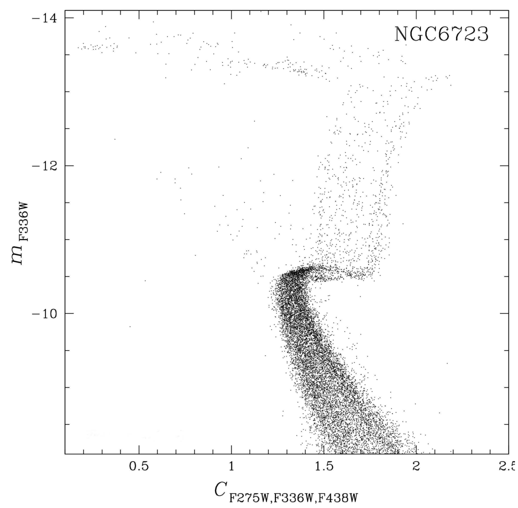

Fig. 2. The m_{F336W} vs $C_{\mathrm{F275W,F336W,F438W}}$ pseudo-CMD of the globular NGC 6723.

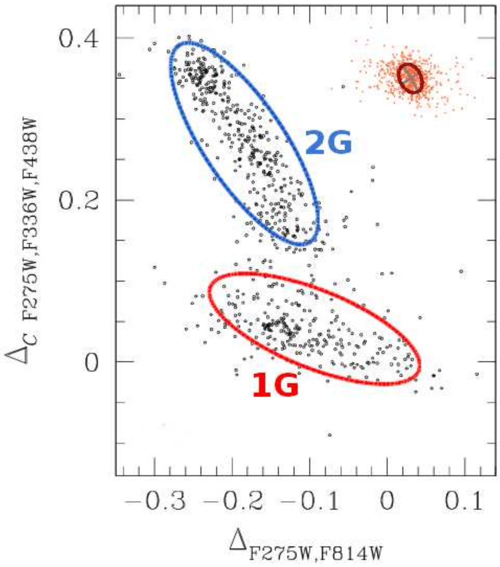

Fig. 3. Chromosome map of RGB stars of NGC 6723. In red and blue are highlighted the 1G and 2G stars (Milone et al. 2017).

reason, 1G stars, that are O- and C-rich, but N-poor, are faint in F275W and F438W, but bright in F336W; *vice-versa*, N-rich, O-,C-poor 2G stars are bright in F275W and F438W, but faint in F336W. As a consequence, 1G stars are, on average, redder than 2G stars in the $m_{F275W} - m_{F336W}$ CMDs, but bluer than 2G stars in the $m_{F336W} - m_{F438W}$ (Fig. 1). Combining these two colors in a pseudo-color $C_{F275W,F336W,F438W} = (m_{F275W} - m_{F336W}) - (m_{F336W} - m_{F438W})$, it is possible to maximize the separation between the different populations hosted by a GC (Fig. 2).

Milone et al. (2017) used an innovative tool, the so-called *chromosome map*, to identify MPs along the red-giant branch (RGB) of 57 GCs. The chromosome maps are pseudo-two-color diagrams that allow us to maximize the separation between the 1G and 2G stars (see Fig. 3). Simple chromosome maps, where it is possible to identify only two main groups of stars (1G/2G), are typical of Type I GCs, i.e. GCs hosting stars having on average the same metallicity (e.g., NGC 2808, Milone et al. 2015b). More complex chromosome maps are associated to Type II GCs. These GCs host RGB stars (red RGB) that are enriched in iron and s-process elements (e.g., M 2, Milone et al. 2015a). Moreover, groups having different metallicity contents present their own Na-O anti-correlation (see Fig. 4), suggesting that a more complex mechanism is behind the formation of this type of GCs.

3. Summary

In the previous sections, I have summarized the photometric evidence we have of MPs in GCs. In general, we have found that MP phenomenon differs from cluster to cluster, but that all the Galactic GCs so far analyzed host at least two stellar generations, characterized by stars having different light elements abundances and helium content. Different populations form discrete sequences in the UV and optical CMDs and two-colors diagrams (Piotto et al. 2015; Milone et al. 2015a,b, 2017). Thanks to UV photometry, we can identify and follow the different populations among different CMDs and at all the evolutionary stages. It allows us to derive, for example, the relative age between the 1G and 2G stars (Nardiello et al. 2015), the dynamical and kinematic properties of MPs (Bellini et al. 2015; Simioni et al. 2016), the horizontal branch properties of the different GCs (Brown et al. 2016; Tailo et al. 2017).

The observational scenario is very complex and we have still not a solution to the problem of how MPs formed. The knowledge of still missing information on MPs (helium content, relative ages, radial distributions, etc.) will be crucial to understand the mechanisms of formation and evolution of GCs, of their stellar populations and of the Milky Way itself.

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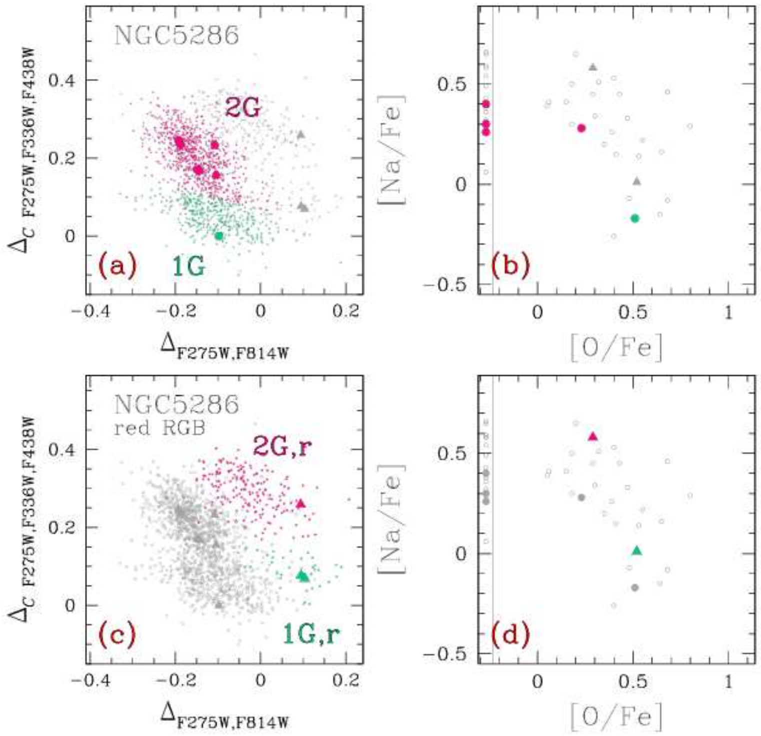

Fig. 4. Chromosome map of RGB stars of NGC 5286. Panel (a) shows the 1G (green) and 2G (magenta) RGB [Fe/H]-normal stars. Green and magenta circles are the stars studied spectroscopically by Marino et al. (2015) and shown in panel (b). Panel (c) shows the 1G and 2G RGB [Fe/H]-enriched stars, while panel (d) shows the Na-O anti-correlation for the stars studied spectroscopically by Milone et al. 2015.

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