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Multiple populations in Globular Clusters from multi-wavelength *HST* photometry

A. P. Milone

Research School of Astronomy and Astrophysics, The Australian National University, Cotter Road, Weston, ACT, 2611, Australia, e-mail: milone@mso.anu.edu.au

Abstract. Recent papers, based on *Hubble Space Telescope* (*HST*) multi-wavelength photometry, have dramatically changed the traditional view of the color-magnitude diagram (CMD) of globular clusters (GCs). Appropriate combination of ultraviolet, visual, and near infrared (NIR) photometry have revealed multiple stellar populations along the entire CMD, from the bottom of the main sequence (MS) up to the the sub-giant (SGB), the red-giant branch (RGB) and even along the horizontal-branch (HB). In this paper I will use NGC 2808 as a prototype to illustrate the typical features of the multiple populations in GCs and to get information on their chemical composition.

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

1. Introduction

The distribution of stars in the CMDs of GCs has been always considered as the best approximation of a single isochrone and has been widely used to test the models of stellar structure and evolution. For a long time, the similarity between GCs and simple stellar populations has been supported by the fact that, when observed in CMDs made with visual colors and magnitude, RGB, SGB, and MS stars seem to distribute along single sequences, whose broadening is consistent with photometric errors only. As an example, high-accuracy photometry of the nearby GC NGC 6397 obtained by Richer et al. (2006) by using five days of time on the *HST* has revealed that all the cluster sequences are narrow and well defined in their ultra-deep $m_{\rm F606W}$ vs. $m_{\rm F606W} - m_{\rm F814W}$ CMD.

The traditional picture of GCs as prototype of single isochrones has been challenged only a few years ago by the discovery of a triple MS in NGC 2808 (Piotto et al. 2007, see also D'Antona et al. 2005) and a split SGB in NGC 1851 (Milone et al. 2008). These multiple sequences have been observed in visual CMDs and have been interpreted as distinct populations with different stellar structure. Specifically, multiple MSs have been connected with stellar populations with different helium abundance, (D'Antona et al. 2002; Norris 2004), while the double SGB is associated with different C+N+O content (Cassisi et al. 2008; Ventura et al. 2009).

Before then, multiple SGBs (Lee et al. 1999) and MSs (Anderson 1997; Bedin et al. 2004) have been observed in visual filters only in ω Centauri, that due to its unusual

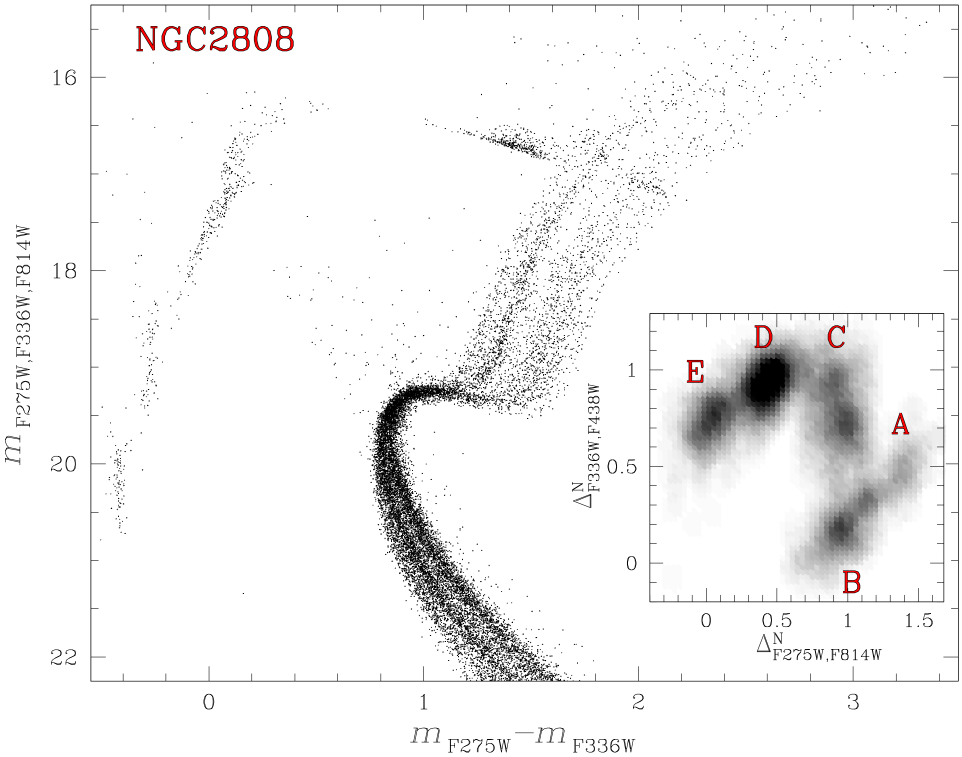

Fig. 1. CMD of NGC 2808 obtained from the $m_{F275W,F336W,F438W}$=(m_{F275W} + m_{F336W} + m_{F814W})/3 magnitude and the $m_{F275W} - m_{F336W}$ color. The inset shows $\Delta^N_{m_{F336W}-m_{F438W}}$ vs. $\Delta^N_{m_{F275W}-m_{F336W}}$ of RGB stars and reveals the five main populations (A–E) of this cluster.

CMD, large mass, and extreme chemical composition was not considered as a genuine GC.

In contrast, it is well known since several decades that nearly all the GCs exhibit internal variation in some light elements, including C, N, O, and Na (see reviews by Kraft 1994 and Gratton et al. 2004). More recently, it has been discovered that stellar populations with different light-element abundance distribute along distinct RGBs in CMDs made with ultraviolet photometry. Indeed the *U*-Johnson filter, (Marino et al. 2008) and the *u*-Strömgren ones (Grundahl et al. 1998; Yong et al. 2008) are very sensitive to the star-to-star nitrogen variations of GCs.

2. The modern view of the CMD of a GC.

Multi-wavelength *HST* photometry has shown that the CMD of all the studied GCs is made of two or more intertwined sequences that can be followed continuously from the hydrogen-burning limit up to the RGB tip (Milone et al. 2012a,b). These sequences correspond to stellar populations with different chemical composition. Most of these discoveries have been obtained by using the method developed by Jay Anderson (see Anderson et al. 2008 and references therein) that allows high-precision photometry from images taken with the Ultraviolet and Visual (UVIS) and the NIR channel of the Wide Field Camera 3 (WFC3) of *HST*.

The phenomenon of multiple populations has been widely investigated in NGC 2808 from both spectroscopy (e.g. Carretta et al. 2006; Marino et al. 2014; Carretta 2015) and photometry (e.g. D'Antona et al. 2005; Piotto et al. 2007; Milone et al. 2012a, 2015a) and in the following we will consider this

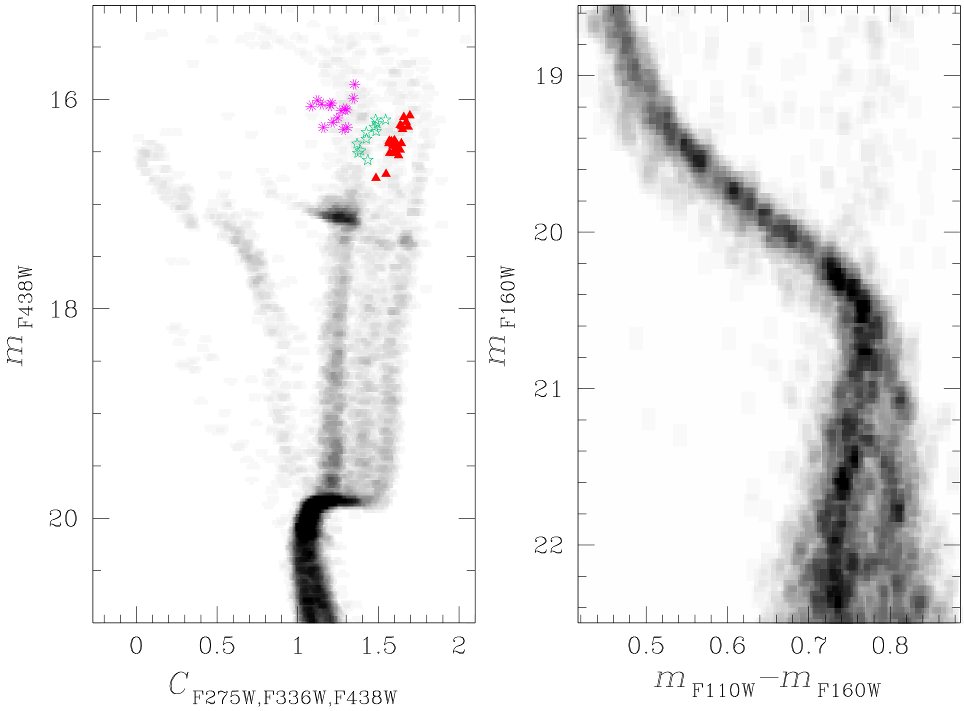

Fig. 2. *Left panel:* m_{F438W} vs. $C_{F275W,F336W,F438W}$ Hess diagram of NGC 2808 from Milone et al. (2015a). The three distinct groups of AGB stars have been represented with magenta, aqua, and red symbols. *Right panel:* Hess diagram of the m_{F160W} vs. $m_{F110W} - m_{F160W}$ CMD from NIR/WFC3 photometry (Milone et al. 2012a).

object as a prototype to illustrate the typical features of the multiple populations in GCs.

Figure 1 reveals that the multiple sequences show a complex pattern along the CMD of NGC 2808. While the MS exhibits three distinct populations, the SGB seems quite narrow and well defined. Suddenly, the multiple sequences reappear at brighter luminosity, where they define distinct RGBs.

The multiple MSs and RGBs of NGC 2808 can be detected in a large variety of diagrams made with several combinations of colors and magnitudes. In particular the $m_{F336W} - m_{F438W}$ color is very efficient to identify stellar populations with different nitrogen abundance, while $m_{F275W} - m_{F814W}$ is appropriate to separate stars with different content of helium and oxygen. In order to combine information for both colors, Milone et al. (2015b) have introduced the pseudo two-color diagram plotted in the inset of Fig. 1 which maximizes the separation among the stellar populations along the RGB and the MS. This diagram has made it possible to discover at least five and seven populations in NGC 2808 and M 2, respectively.

The $C_{F275W,F336W,F438W} = (m_{F275W} - m_{F336W}) - (m_{F336W} - m_{F438W})$ pseudo-color (Milone et al. 2013) is another efficient tool to identify multiple populations (see Fig. 2 for NGC 2808). Intriguingly, in this diagram asymptotic-giant branch (AGB) stars distribute along distinct sequences thus demonstrating that the AGB of NGC 2808 is not consistent with a single isochrone. A spectroscopic study of these stars by Marino et al. (in preparation) will allow us to understand whether the three AGBs correspond to stellar populations with different chemical composition or not.

Multiple sequences have been rarely detected along the lower part of the MS because observational limits make it hard to get precise photometry of very faint and red stars in optical and ultraviolet bands. Very recently, WFC3/NIR has revealed multiple MSs of M-dwarfs in some GCs thus opening a new window in the study of multiple populations.

The right panel of Fig. 2 shows that the distinct stellar populations of NGC 2808 have different colors and magnitudes in the $m_{\rm F160W}$ vs. $m_{\rm F110W} - m_{\rm F160W}$ CMD. The three MSs are visible along the upper MS and merge together at the luminosity of the MS knee while at fainter magnitudes, only two MSs can be identified. A blue, more populated MS, which is connected with the primordial-helium population observed by Piotto et al. (2007) in the upper MS, and a redder MS that corresponds to the two helium-rich MSs discovered by Piotto and collaborators.

Besides identifying the number, the ratio, and the spatial distribution of the multiple populations in GCs, multi-wavelength photometry has allowed to set constraints on the helium and light-element abundance of each population. Indeed, once the distinct populations have been selected from the diagrams shown in Fig. 1 and 2 it is possible to compare their colors with synthetic spectra and infer the relative abundance of He, C, N, and O. Specifically, the five populations of NGC 2808 have different helium content, from primordial (Y$\sim$0.25) up to Y$\sim$0.38. The He abundance correlates with N and Na, anti-correlates with C and O, and is the main responsible of the HB morphology. I refer to the papers by Milone et al. (2015a,b) for details. It should be noted that spectroscopic determinations of the He content is only feasible in rare cases for a small subset of stars and GCs (e.g. Marino et al. 2014). In contrast, photometry of multiple MSs and RGBs is providing, for the first time, precise determinations of the He abundance in a large number of clusters. The knowledge of the helium distribution in GCs is a crucial and still-missing ingredient to understand the nature and the origin of these enigmatic stellar systems and of their stellar populations.

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