WFPC2 UV survey of Galactic Globular Clusters. The Horizontal Branch temperature distribution.

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Abstract Ultraviolet observations are the best tool to study hot stellar populations which emit most of their light at short wavelengths. As part of a large project devoted to the characterization of the UV properties of Galactic globular clusters (GGCs), we collected mid/far UV and optical images with the WFPC2@*HST* for 31 GGCs. These clusters cover a wide range in metallicity and structural parameters, thus representing an ideal sample for comparison with theoretical models. Here we present the first results from an ongoing analysis aimed at deriving the temperature distribution of Horizontal Branch stars in GGCs.

Keywords Globular clusters: hot stars; Horizontal Branch; NGC 5139; NGC 6293

1 Introduction

In old stellar populations like Galactic globular clusters (GGCs), the hottest stars are Blue Stragglers (BSS), Horizontal Branch (HB), Post-Early Asymptotic Giant Branch (PEAGB) and AGB-manqué whose spectral emission peaks at effective temperatures higher than $\sim 6,000\,K$ (Ferraro et al. 2012; Moehler et al. 2007; Ferraro et al. 1997a; Sweigart 1987). Therefore these stars mostly emit in the ultraviolet (UV) part of the electromagnetic spectrum (Moehler et al. 1995; de Boer 1985). Since the Earth's atmosphere is almost completely opaque to this wavelength regime, any campaign for the observation of hot stars in UV must be performed using space facilities like, for instance, the Hubble Space Telescope (*HST*) or the Galaxy Evolution Explorer (GALEX). Unfortunately, the theoretical models describing the evolution of stars of the earliest spectral types still suffer from many uncertainties which are also due to the absence of a complete and homogeneous sample of UV emitters. Therefore, the UV observation of hot stars in GGCs is extremely important in order to compare data and evolutionary models in observational planes not hampered by critical color - effective temperature ($T_{\rm eff}$) transformations (Dalessandro et al. 2013a; Schiavon et al. 2012; Dalessandro et al. 2011; Ferraro 2006b; Cassisi et al. 2004; Ferraro et al. 2003, 1998, 1997b).

One of the most interesting stellar evolutionary sequences that still wait to be fully understood is the HB. It is commonly accepted that metallicity is the first parameter driving the Horizontal Branch morphology. Indeed, metal-rich GGCs typically have red HBs while metal-poor ones have more extended and blue HBs. However, there are several clusters with the same metallicity showing remarkable differences in Horizontal Branch morphology: nice examples are the couples NGC 6388 - NGC 5927, M 3 - M 13 and M 15 - M 92. Therefore, metallicity alone is not able to explain the observation of the complex HB zoology in GGCs (Freeman & Norris 1981). This issue, known as the '2nd parameter' problem, has focused the attention of several authors in the last years (Gratton et al. 2010; Dotter et al. 2010; Catelan 2009; Lee et al. 1994; Fusi Pecci et al. 1993), but the solution is not obvious because many mechanisms play a role in shaping the color distribution of HB stars, such as mass loss, age and He abundance (Rood 1973). Nonetheless, now there is a general con-

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sensus about the fact that age is the main global 2nd parameter (Gratton et al. 2010; Dotter et al. 2010).

The HB temperature extension can be an efficient way to parametrize the HB morphology and therefore to study the '2nd parameter' problem. This approach has been already attempted by Recio-Blanco et al. (2006) and, later on, by Babu et al. (2009), who used optical CMDs for their analysis. However, temperature derived from optical filters only, can be underestimated by more than $10,000\,K$ in the case of very extended HBs (see the case of NGC 2808, Dalessandro et al. 2011). This demonstrates the difficulties of deriving properties of hot HB populations from pure optical data. Indeed in the optical plane, stars move down to the blue HB tail either because the bolometric correction increases or because stellar luminosity decreases. For very blue HB stars (like Blue Hook stars) both the above quantities are changing and optical colors cannot provide a reliable estimate of $T_{\rm eff}$.

As a part of a large project aimed at characterizing the UV properties of GGCs (Sanna et al. 2014; Dalessandro et al. 2013b,a; Contreras Ramos et al. 2012; Dalessandro et al. 2012; Sanna et al. 2012; Schiavon et al. 2012; Dalessandro et al. 2011, 2009) we present here some preliminary results coming from the photometric analysis of UV observations of 31 GGCs obtained with the Wide Field and Planetary Camera 2 (WFPC2) and finalized to accurately derive the HB temperature distribution and extension.

2 Observations, reduction and data analysis

A large dataset [1] of mid/far UV and optical images, in the filters $F160BW, F170W, F255W, F300W, F336W$ and $F555W$, has been collected with the WFPC2 onboard *HST* and has been complemented with a few images collected in the $F150LP$ filter with the Solar Blind Channel (SBC) of the Advanced Camera for Survey (ACS@*HST*), for a total sample of 31 GGCs. The targeted GGCs cover a wide range of metallicity ($-2.2 <$ [Fe/H] < -0.4) and concentration parameter ($0.8 < c < 2.5$).

Every WFPC2 frame was pre-processed through the standard *HST*/WFPC2 pipeline for bias subtraction, dark correction and flat fielding and corrected for specific instrument-induced variation of the signal ('34th row' effect and Pixel Area Correction, Baggett et al. 2002) across the field of view (FoV). Then, we have extracted single images from the four-chip mosaic of the WFPC2 and, for each given chip and filter, we have combined them by using specific IRAF tasks and cosmic-ray rejection algorithms [2], in order to obtain a combined median image with high S/N.

The photometric analysis of the combined image has been performed with DAOPHOT IV/ALLSTAR (Stetson 1987). An analytic point spread function (PSF) has been evaluated on each image by selecting bright, isolated stars uniformly distributed over the entire chip area. Once the instrumental catalogs have been obtained for the different chips and filters, they have been geometrically matched by using DAOMATCH/DAOMASTER (Stetson 1994), in order to build a master catalog. Stars in the master catalog are then force-fitted onto single images by using ALLFRAME (Stetson 1994), eventually obtaining an instrumental catalog for each filter/chip combination. For every catalog we computed and applied the aperture correction by using DAOGROW (Stetson 1990) and the Charge Transfer Efficiency (CTE) and UV loss by means of the equations provided by Dolphin (2009). Instrumental magnitudes were finally calibrated to the VEGAMAG system by following the prescriptions and the zero points provided in the WFPC2 Instrument Science Report 97-01 (Baggett et al. 1997).

3 UV-optical CMDs: the case of ω *Cen*

Among the surveyed targets particular interest is undoubtedly reserved to ω *Centauri* (NGC 5139, Sollima et al. 2005; Bedin et al. 2004; Ferraro et al. 2004). This stellar system hosts at least six sub-population of stars with different α-elements and iron abundances (Pancino et al. 2011; Gratton et al. 2011; Bellini et al. 2010; Calamida et al. 2009; Johnson et al. 2009; Sollima et al. 2007, 2004; Origlia et al. 2003), and with significant spread in helium (Piotto et al. 2005). As far as the hot stellar populations are concerned, ω *Cen* shows, together with NGC 2419 (Dalessandro et al. 2008), the largest population of BSSs (Ferraro et al. 2006a), as well as one of the most extended HB (D'Cruz et al. 2000).

Due to its large half-light radius of 5 arcmin (Harris 1996, 2010 edition), 13 fields around the center of ω *Cen* have been imaged in the WFPC2 UV survey. Images were collected in two filters: $F170W$ and $F555W$.

The final CMD of the total FoV of ω *Cen* is shown in Fig. 1. In this plane we can distinguish at least three well defined sequences. The vertical strip at $(m_{F170W} - m_{F555W}) \approx 3.5$ is a combination of the bright Red Giant Branch (RGB) and AGB stars. The presence of

[1] Program GO 11975, PI F. R. Ferraro.

[2] Cosmic ray contamination is particularly important for long-exposed UV images.

such cool stars in this UV plane is due to the spectral response of the filter F170W which suffers from a quite important 'red-leak' (WFPC2 Instrument Handbook, August 2008). The diagonal strip extending from the base of the RGB to $m_{F170W} \sim 16.5$ is populated by the brightest BSSs in our FoV [3]. The brightest and hottest stars in the $(m_{F170W}, m_{F170W} - m_{F555W})$ CMD are HB and post-HB stars. The HB of $\omega\,Cen$ is almost homogeneously populated from red ($m_{F170W} - m_{F555W} \lesssim 3$) to extremely blue colors ($m_{F170W} - m_{F555W} \approx -2$). Fig. 1 shows that at the hot end of the HB there is an uprising sequence populated by Blue Hook stars ($m_{F170W} \lesssim 17, (m_{F170W} - m_{F555W}) \gtrsim -2$, D'Antona et al. 2010; Cassisi et al. 2009).

Other than for $\omega\,Cen$, the data analysis has been completed for nine additional GGCs in the survey. The relative CMDs are shown in Fig. 2. They display features (RGB, HB, BSS) similar to those already described for the CMD of $\omega\,Cen$. Cluster-to-cluster differences of course may appear, in particular each cluster shows a quite different HB extension (Lagioia et al. 2014, in preparation).

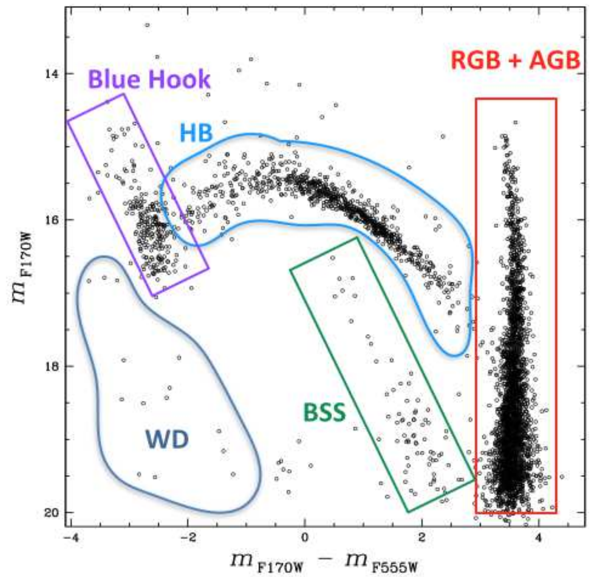

Fig. 1 $(m_{F170W}, m_{F170W} - m_{F555W})$ CMD of $\omega\,Cen$. Encircled areas emphasize the different evolutionary sequences: RGB+AGB = Red Giant Branch + Asymptotic Giant Branch, BSS = Blue Stragglers, HB = Horizontal Branch, Blue Hook, WD = White dwarfs.

4 The HB temperature distribution of NGC 6293

As stated in Sect. 1, one of the scientific goals of the WFPC2 UV survey is to derive the temperature distribution of HB stars in the observed clusters. In order to accomplish this task we must compare the observations with suitable theoretical models. As detailed in Dalessandro et al. (2013a, 2011) and Salaris et al. (2013), there are several important points that should be properly taken into account: the effect of radiative levitation, α-element variation and the presence of sub-populations with different He abundance. In this sense $\omega\,Cen$ represents a very interesting case but it needs particular caution because of its complexity. Among the clusters already available (see Figures 1 and 2) we decided to start our analysis with a relatively simple case: NGC 6293. This GGC has apparent distance modulus $(m - M)_V = 16.00$ and reddening $E(B - V) = 0.36$ (Harris 1996, 2010 edition) and it is the most metal-poor cluster observed in the Galactic bulge ([Fe/H] = −1.73, Valenti et al. 2007). The optical CMD of this cluster is shown in Fig. 3.

Because of the 'red-leak' of the $F170W$ filter (Sect. 3) some of the coolest HB stars may overlap the RGB sequence in the far UV - optical plane. For this reason we first selected HB stars in the optical CMD

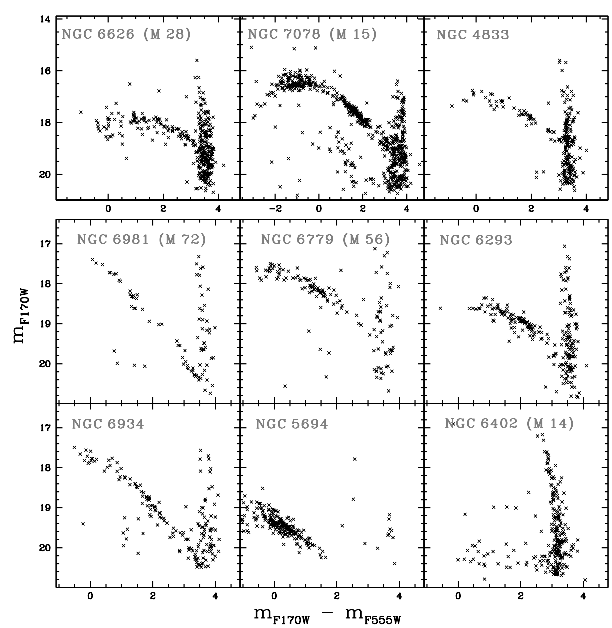

Fig. 2 $(m_{F170W}, m_{F170W} - m_{F555W})$ CMD of nine out of 31 GGCs present in out survey.

[3] We have identified the BSSs by matching our catalog with the candidate BSSs selected by Ferraro et al. (2006a).

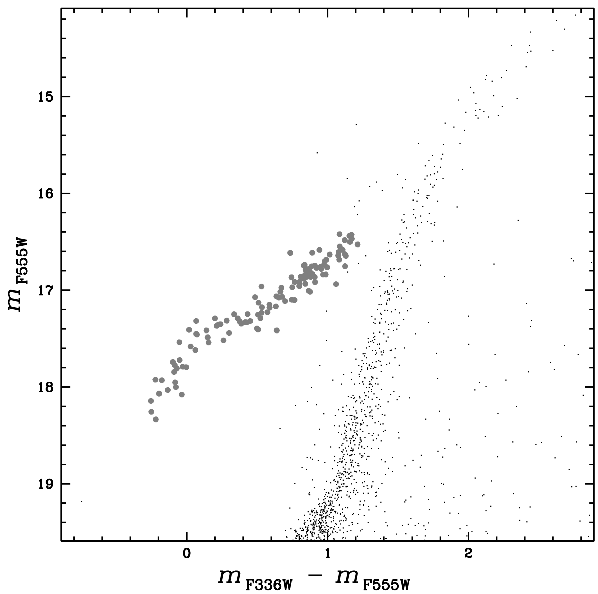

Fig. 3 Optical ($m_{F555W}, m_{F336W} - m_{F555W}$) CMD of NGC 6293. The filled gray circles mark the HB stars selected in this plane.

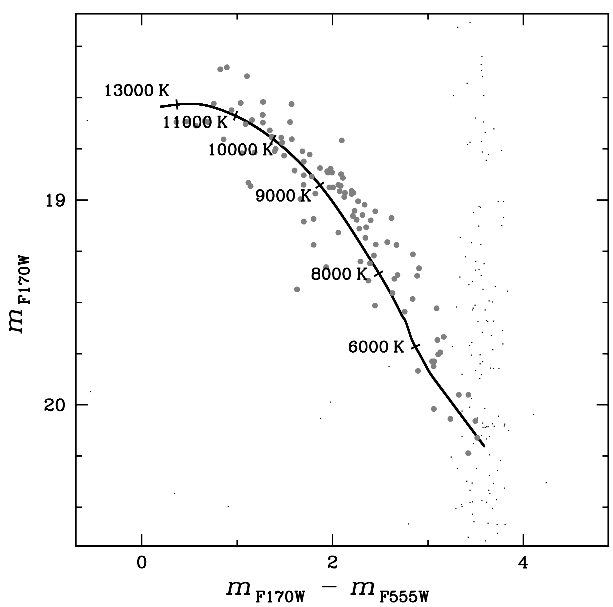

Fig. 4 Far UV - optical ($m_{F170W}, m_{F170W} - m_{F555W}$) CMD of NGC 6293. The filled gray circles correspond to the HB stars selected in the optical CMD (Fig. 3). A ZAHB model, suitably calculated for this cluster (see text for explanation), has been overplotted as a solid black line. Some temperature values along the ZAHB are also marked.

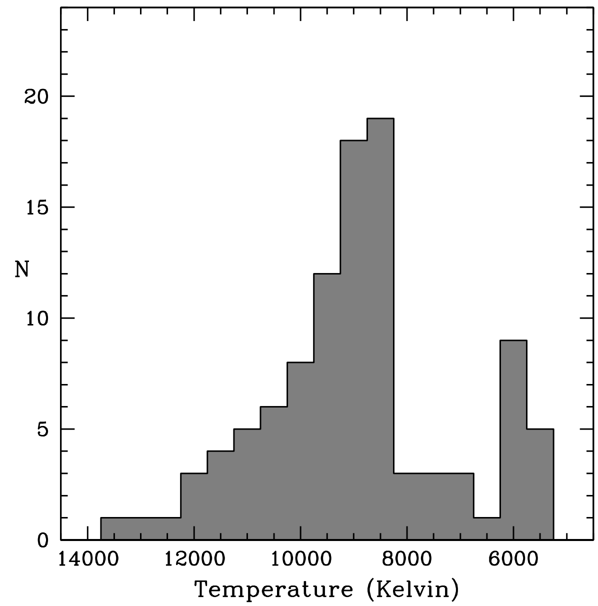

Fig. 5 Histogram of the temperature distribution of HB stars of NGC 6293 obtained from the analysis of the ($m_{F170W}, m_{F170W} - m_{F555W}$) plane.

(filled gray circles in Fig. 3), where the separation between HB and RGB stars at low $T_{\rm eff}$ is clearer. The position of the HB stars in the UV-optical CMD is shown in Fig. 4, where we also plotted the best-fit Zero Age Horizontal Branch (ZAHB) model from the Basti Database (Pietrinferni et al. 2006), computed by assuming $[{\rm Fe/H}] = -1.84$, $[\alpha/{\rm Fe}] = 0.4$, $(m-M)_0 = 15.2$ and reddening $E(B-V) = 0.36$. It is important to notice that, because of the spectral response of the $F170W$ filter, the reddening correction is a strongly variable function of the temperature (color) of the star and it therefore requires particular attention. A crucial step in our analysis is the search for variable stars populating the HB. Indeed, they could considerably affect the determination of the HB temperature distribution. According to the Catalogue of Variable Stars in Galactic Globular Clusters (Clement et al. 2001, 2013 update), NGC 6293 is known to host five RR Lyrae stars but only three of them fall in our WFPC2 FoV. Moreover, their position in the Clement's catalog is derived from ground-based observations and we were not able to unambiguously identify them in our high-resolution HST catalog. Their inclusion in our HB sample, however, does not affect at all our analysis.

Following the procedure described in Dalessandro et al. (2011) we derived the temperature of each star by projecting its color onto the ZAHB model. The temperature is the result of the interpolation between the two closest points of the ZAHB. The distribution obtained is shown in Fig. 5.

We observe that the histogram spans a temperature interval going from $\sim 5000\,K$ to $\sim 13000\,K$ and that the mode of the distribution is located at $\sim\ 8500\,K$. More than 50% of the stars have a temperature higher than the peak value. To establish how much the 'red-leak' affects the estimate of temperature of the cold HB stars in the UV-optical plane, we determined the temperature of the same stars also from the optical $(m_{F255W} - m_{F555W}, m_{F255W})$ CMD. Then, we determined the difference between the two temperature estimates. We found that the average differences of the HB stars colder and hotter than $\sim 8000\,K$ agree each other within the errors.

Unfortunately, neither photometric nor spectroscopic temperature estimates for the HB stars of NGC 6293 are available in literature. Therefore, no direct comparison can be done with our data. Nevertheless, Dalessandro et al. (2011), by using the same set of theoretical models described in the present paper, found that the photometric estimates of the HB star temperatures of the cluster NGC 2808 are fairly consistent with the temperatures derived from the spectroscopic observations by (Moehler et al. 2004).

5 Summary

We have analyzed far/mid UV-optical images for ten out of 31 GGCs collected within the WFPC2 UV survey. The main task of this analysis is to derive the extension and the temperature distribution of the HB of the targeted clusters taking advantage of the UV data. The use of UV bands is the best tool to accomplish our task since, for stars with high $T_{\rm eff}$, the bolometric correction decreases and the stellar luminosity increases with respect to the optical bands. It has been shown, indeed, that the temperatures of extended HBs derived from a combination of pure optical filters can be underestimated by $10,000 - 15,000\,K$ (Dalessandro et al. 2011). We used NGC 6293 as a starting point in our analysis, determining the temperature distribution of its HB stars. We are now applying this analysis to other GGCs in our sample with extended HBs, like $\omega\,Cen$ and M 15.

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