ON THE RADIAL DISTRIBUTION OF HORIZONTAL BRANCH STARS IN NGC 2808

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ABSTRACT

We present accurate new ultraviolet and optical BVI photometry for the Galactic globular cluster NGC 2808 based on both ground-based and archival Hubble Space telescope imagery. From this we have selected a sample of ~2000 Horizontal Branch (HB) stars; given the extensive wavelength range considered and the combination of both high angular resolution and wide-field photometric coverage, our sample should be minimally biased. We divide the HB stars into three radial bins and find that the relative fractions of cool, hot, and extreme HB stars do not change radically when moving from the center to the outskirts of the cluster. The difference is typically smaller than ~2σ. These results argue against the presence of strong radial differentiation among any stellar subpopulations having distinctly different helium abundances. The ratio between HB and red giant (RG) stars brighter than the ZAHB steadily increases when moving from the innermost to the outermost cluster regions. The difference is larger than ~4σ and indicates a deficiency of bright RGs in the outskirts of the cluster.

Key words: globular clusters: general – globular clusters: individual (NGC2808) – stars: horizontal-branch

1. INTRODUCTION

The Galactic globular cluster (GGC) NGC 2808 is a very interesting stellar system. Space- and ground-based optical photometry show that both the red giant branch (RGB) and the main sequence (MS) show spreads in color larger than can be explained by intrinsic photometric errors (Bedin et al. 2000). However, recent accurate high-resolution spectroscopic measurements of ~120 red giants (RGs; Carretta 2006) indicate that no spread in metal abundance is present ([Fe/H] = −1.10 ± 0.065). The observational scenario was enriched by the detection of a fringe of stars blueward of the canonical MS by D’Antona (et al. 2005). This evidence was solidified by the identification of a triple MS by Piotto et al. (2007) using accurate photometry of an off-center field collected with the Advanced Camera for Surveys (ACS) on board the Hubble Space Telescope (HST). The authors proposed that this cluster had experienced different episodes of star formation with significant helium enrichment (0.30 ≤ Y ≤ 0.40).

NGC 2808 also shows an extended blue horizontal branch (HB) with multiple distinct components, and a helium enrichment sufficient to explain the presence of multiple MSs that had already been proposed to explain this morphology (D’Antona et al. 2002, 2005; Lee et al. 2005). More recently, D’Ercole et al. (2008) have performed detailed simulations of the formation and the dynamical evolution of GCs hosting multiple stellar populations. They found that a substantial fraction of first generation stars are lost during the early cluster evolution. Moreover, the resulting radial profile of the ratio between second and first generation MSs is characterized by a flat trend in the inner regions with a decrease (i.e., the first generation relatively more important compared to the second) in the outer cluster regions (see especially their Figure 18).

From the analysis of optical and UV Wide Field Planetary Camera 2 (WFPC2) images, Castellani et al. (2005) found that the ratio between HB and RG stars brighter than the HB luminosity level (the classical R parameter) in NGC 2808 increases when moving from the core to the outermost regions. A deficiency of bright RGs in this cluster was suggested by Sandquist & Martel (2007) on the basis of HST images. Peculiar radial distributions of HB stars in ω Centauri have been suggested by Castellani et al. (2007). More recently, Zoccali et al. (2009) argued that the fainter (peculiar) of the two subgiant branches detected in NGC 1851 (Milone et al. 2008; Cassisi et al. 2008) disappears at radial distances larger than 2.4 arcmin.

In this investigation we focus our attention on the luminosity function of HB stars in NGC 2808.

2. OBSERVATIONS AND DATA REDUCTION

In order to address these issues we took advantage of several UV and optical data sets collected with both HST and ground-based telescopes. These include UV data from the Space Telescope Imaging Spectrograph (STIS, 8511; PI: P. Goudfrooij) in far-UV (FUV, F25QT Z; λc = 1590, FWHM = 220 Å) and near-UV (NUV, F25CN/270, λc = 2700, FWHM = ...
Individual images cover a field of view (FOV) of 25′′×25′′, and the pixel scale is 0′′0248 pixel−1. The entire data set consists of 18 FUV and 18 NUV images with exposure times ranging from 480 to 538 s located across the cluster center (pointing α, see Figure 1). We also used data from the ACS High-Resolution Channel (ACS HRC, 10335; PI: H. Ford) in F435W (24×135 s) and F555W (4×50 s). Individual images cover a FOV of 29′′×26′′ and the pixel size is 0′′028×0′′025. These images, too, are located across the cluster center (pointing β, Sandquist & Martel 2007). We also used data collected with ACS Wide Field Camera (ACS WFC, 10775; PI: A. Sarajedini) in F606W (5×360 s and 1×23 s) and F814W (5×370 s + 1×23 s). Individual images span 202′′×202′′ at 0′′05 pixel−1; these are slightly dithered and are also located across the cluster center (pointing δ). These data were supplemented with optical/UV data images from the WFPC2: pointing γ, located near the cluster center—F218W (1×1600 s + 1×1700 s), F439W (2×230 s + 1×50 s), F555W (1×7 + 1×50 s) from proposal 6095 (PI: S.G. Djorgovski; also Bedin et al. 2000; Castellani et al. 2006; Sandquist & Hess 2008); pointing δ, also close to the cluster center and partially overlapping γ—F336W (2×3600 s), F555W (3×100 s + 2×7 s), F814W (3×120 s + 2×3 s) from proposal 6804 (PI: F. Fusi Pecci); pointing ε, a couple of arcminutes southwest of the cluster center—F336W (4×1600 s), F555W (4×900 s + 3×100 s + 2×7 s), F814W (4×700 s + 3×120 s + 2×3 s), also from proposal 6804.

For wider coverage of the cluster regions, we collected multiband (UBVI) ground-based archival data covering ≈20′×15′ around the center of the cluster (pointing ζ; see Figure 1). The dark area around the cluster center marks the high density cluster regions. A total of 573 CCD images collected between 1987 January and 2002 February were reduced, but not all of these could be calibrated because of an insufficiency of standard-star observations. Moreover, since some of these data were acquired with mosaic cameras, and since even for single-chip cameras not all telescope pointings were the same, no individual star could be measured in all images. To summarize, calibrated photometry for any given star is available from at most 18 CCD images in U, 26 in B, 66 in V, and 59 in I.

Photometric reduction of the STIS images was done with ROMAFOT, while photometry of pointing γ was obtained with both ROMAFOT and DAOPHOT/ALLFRAME. The photometry for all the other data was carried out with DAOPHOT/ALLFRAME. The final catalog includes ~379,000 stars with at least one measurement in two or more different optical bands, ~100,000 stars with at least one U or F336W measurement, and ~4900 stars with at least one shorter-wavelength UV measurement (FUV, NUV, and F218W).

The WFPC2 photometry was kept in the Vega system following the prescriptions suggested by Holtzman et al. (1995). The STIS photometry was referred to the Vega system following the prescriptions by Brown et al. (2001) and Dieball et al. (2005). For homogeneity the ACS F435W, F555W, F606W, and F814W magnitudes were transformed into WFPC2 F435W, F555W, and F814W magnitudes on the basis of common stars. Finally, for the same reason, the ground-based UBVI magnitudes were transformed into the WFPC2 F336W, F435W, F555W, and F814W systems. The typical accuracy of the calibration is of the order of 0.02 mag for all the quoted bands. Here, however, we would like to stress that the results of the present paper depend upon star counts in different, easily recognized zones of the color–magnitude diagrams (CMDs). Accuracy of the absolute calibrations is not a serious consideration for the present analysis.

3. RESULTS AND DISCUSSION

To identify HB stars near the center of the cluster we adopted the optical and UV results from HST. The reason is twofold. (1) Detectors with a high angular resolution are mandatory for accurate photometry in crowded cluster regions. Note that the core radius and the half mass radius of NGC2808 are $r_c = 0.26$ and $r_h = 0.76$ arcmin (Harris 199613), respectively. Fortunately, these regions are covered by data sets collected with four different detectors (STIS, ACS HRC, ACS WFC, WFPC2). (2) The optical-UV colors are highly sensitive to effective temperature, providing the opportunity to properly select hot HB stars. For these reasons we gave the highest priority to CMDs based on optical-UV magnitudes. In particular, we adopted F555W, FUV-F555W; F555W,NUV-F555W; F555W, F218W-F555W; and F555W, F336W-F555W CMDs.14 Data plotted in Figure 2 show that the difference in color between Extreme HB (EHB) and RG stars ranges from ~6 (panel d) to ~14 mag (panel a). Moreover, they also show that in the UV bands (panels a, b, c) we detected not only HB stars but also Blue Stragglers (17.5 ≲ F555W ≲ 19, 13 http://physun.physics.mcmaster.ca/ harris
14 Note that we used weighted averages for the magnitudes of stars present in multiple data sets.
1 \lesssim F218W-F555W \lesssim 2), turnoff stars (TO, see the arrow in Figure 2), main-sequence (MS) stars, and a handful of bright RG stars. To our knowledge these are the deepest optical-UV CMDs ever collected for a GC.

Following Castellani et al. (2006) we define red HB (RHB) stars as those with colors redder than the RR Lyrae instability strip and with 15.70 \lesssim F555W \lesssim 16.61 mag. The HB stars bluer than the instability strip range from 15.8 to 21.6 in V or F555W magnitude, and we confirm the finding of Bedin et al. (2000) that they can—with minimal ambiguity—be divided into three subsets by cuts near V \sim F555W \sim 18.26 and 19.95. From brightest to faintest, we refer to these three subgroups as EBT1, EBT2, and EBT3. The stars belonging to EBT3 have been called by different names in the literature (Moehler et al. 2004; Dalessandro et al. 2008), but we adopt our present nomenclature because we do not want to address their physical nature in this investigation. Note that in panel d of the RR Lyrae gap is not clearly identified, so to distinguish RHB from EBT1 stars we adopted either the F435W-F555W or the F555W-F814W color.

To avoid possible biases in the selection criteria and to improve the coverage of the inner cluster regions we also considered purely optical CMDs based on HST data: in particular, F555W, F439W-F555W and F555W, F555W-F814W. Finally, to cover the area between the inner regions covered by HST data and the tidal radius (r_t \sim 15.5 arcmin) we adopted the F555W, F555W-F814W and the F555W, F336W-F814W CMDs inferred from ground-based photometry (see panels c, d of Figure 3). Data plotted in Figure 3 show that the current optical photometry provides very good sampling from the tip of the RGB down to a couple of magnitudes fainter than the TO. Despite NGC 2808’s low Galactic latitude (l = 282°, b = -11°, the EBT1, EBT2, and EBT3 samples should be minimally contaminated by field stars, since stars this hot and faint are rare); conversely, RHB stars have F555W-F814W and F336W-F814W colors similar to common field stars.

Data plotted in the pure optical CMDs—panel d of Figure 2 and panels a, b, c of Figure 3—show that only a small fraction of the stars we have identified as probable HB stars could be confused with either MS or RG stars. Another small fraction of the HB sample lies among the stars located between the HB and the MS–RG fiducial cluster sequence. These stars appear to be normal HB stars in optical-UV CMDs. They were labeled “HB peculiar” by Castellani et al. (2006) and are probably either chance blends or physical binaries (Sandquist & Hess 2008).

Overall, we ended up with a sample of \approx 2000 HB stars distributed over the entire body of the cluster. Note that the current sample is almost a factor of two larger than the sample collected by Castellani et al. (2006). To investigate their radial distribution, we split the total sample into three subgroups, namely r \lesssim r_i = 0.59, r_i < r \lesssim r_p = 1.37 and r_p < r \lesssim r_t = 15.5 arcmin. The reason for specifically selecting these radial limits is twofold: (1) each radial bin includes approximately one-third of the entire sample and (2) the two inner radial bins are based on HST data alone.

The left-hand panels of Figure 4 show the Luminosity Function (LF) of the HB stars in the three different radial bins. The observed distributions (dotted lines) were smoothed using a conservative Gaussian kernel with standard deviation equal to three times the formal photometric uncertainties of individual stars to produce the solid curves. The vertical dashed lines show the range in apparent magnitude for the different HB groups, namely the RHB, which dominates the narrow peak, and the three EHB subgroups. These data (see also Table 1) indicate that, within the errors, the four HB subgroups follow the same radial distribution when moving from the center to the outskirts of the cluster. Moreover, more than 50% of all HB stars belong to the blue tail everywhere in the cluster. Data plotted in the right panels of Figure 4 show that F814W-band LFs show very similar trends for the four subgroups when moving from the center to the outermost cluster regions (see also Table 1).

The apparent increase in the relative fraction of RHB stars in the external radial bin is caused by field star contamination. To evaluate their contribution on a quantitative basis we selected a region located well beyond the tidal radius (r \approx 19.4 arcmin), and using both the F555W, F555W-F814W and the F555W, F336W-F814W CMDs we found that we expect \approx 52 \pm 7 field stars in the CMD box we adopted to define the RHB. The uncer-
The number of HB stars per bin and the distributions, while the solid lines the smoothed luminosity function obtained luminosity function in different radial bins. The dotted lines display the observed $F_{\text{W}}$-band (right). From top to bottom the three panels display the $F_{\text{W}}$-band LF

Table 1

| Radius | N(RHB) | N(EBT1) | N(EBT2) | N(EBT3) | N(HB) | N(RGB) | $R^\circ$ |
|--------|--------|---------|---------|---------|-------|--------|----------|
| $r < r_o$ | 217 (37 ± 3%) | 217 (37 ± 3%) | 81 (14 ± 2%) | 69 (12 ± 1%) | 584 | 444 | 1.32 ± 0.08 |
| $r_o < r < r_p$ | 238 (35 ± 3%) | 244 (36 ± 3%) | 112 (16 ± 2%) | 88 (13 ± 1%) | 682 | 340 | 2.01 ± 0.13 |
| $r_p < r < r_t$ | 360 (52 ± 3%) | 164 (24 ± 2%) | 84 (12 ± 1%) | 85 (12 ± 1%) | 693 | 281 | 2.47 ± 0.17 |
| Total | 815 (42 ± 2%) | 625 (32 ± 2%) | 277 (14 ± 1%) | 242 (12 ± 1%) | 1959 | 1065 | 1.84 ± 0.07 |

$F_{\text{W}}$-band LF

The limits adopted in the Table 1 show that the HB counts based on the F555W-band LF

$F_{\text{W}}$-band LF

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Table 1

The HB and RGB Star Counts in Different Radial Bins

| Radius | N(RHB) | N(EBT1) | N(EBT2) | N(EBT3) | N(HB) | N(RGB) | $R^\circ$ |
|--------|--------|---------|---------|---------|-------|--------|----------|
| $r < r_o$ | 273 (41 ± 3%) | 273 (41 ± 3%) | 86 (12 ± 2%) | 40 (6 ± 1%) | 672 | 439 | 1.53 ± 0.09 |
| $r_o < r < r_p$ | 262 (37 ± 3%) | 269 (37 ± 3%) | 124 (17 ± 2%) | 66 (9 ± 1%) | 721 | 344 | 2.10 ± 0.14 |
| $r_p < r < r_t$ | 368 (52 ± 3%) | 180 (25 ± 2%) | 85 (12 ± 1%) | 82 (11 ± 1%) | 715 | 298 | 2.40 ± 0.17 |
| Total | 903 (43 ± 2%) | 722 (34 ± 2%) | 295 (14 ± 1%) | 188 (9 ± 1%) | 2108 | 1081 | 1.95 ± 0.07 |

$F_{\text{W}}$-band LF

The limits adopted in the F814W-band to identify the HB subgroups are: RHB—redder than RR Lyrae and 15.77 < $F_{\text{W}}$ < 15.77, EBT1—bluer than RR Lyrae and 15.77 < $F_{\text{W}}$ < 18.21, EBT2—18.21 < $F_{\text{W}}$ < 19.89, EBT3—19.89 < $F_{\text{W}}$ < 21.50.

Figure 4. Luminosity function of HB stars in the F555W (left) and in the F814W-band (right). From top to bottom the three panels display the luminosity function in different radial bins. The dotted lines display the observed distributions, while the solid lines the smoothed luminosity function obtained using a Gaussian kernel. The vertical dashed lines show the magnitude ranges adopted to select the HB subgroups. The number of HB stars per bin and the relative fractions of HB subgroups are also labeled.

The above experiments indicate that the quantitative HB morphology in NGC 2808 does not show any pronounced radial trend. Moreover, the qualitative HB morphology (i.e., clumps and gaps) also does not change when moving from the very center to the outermost cluster regions, in agreement with the findings of Walker (1999) and Bedin et al. (2000). This evidence indicates either that the physical mechanism(s) driving the origin of the extended blue tail is at work throughout the entire body of the cluster, or that any putative subpopulations within the cluster are well mixed, in contrast with the predictions of D'Ercole et al. (2008; see also Yoon et al. 2008). Moreover, the apparent constancy of the HB with radius suggests that responsibility for the radial change in the ratio of HB to RG stars (Castellani et al. 2006) may lie with the RGs. To validate this working hypothesis we performed detailed counts of bright RGs using $HST$ CMDs for the inner regions (see panel d of Figure 2 and panels a, b of Figure 3), and ground-based CMDs for the area located between the inner regions and the tidal radius (panels c,d of Figure 3). Following Castellani et al. (2006) we adopted $F_{\text{W}}$-band LF and the same radial bins adopted for HB star counts. The field star contamination in the external radial bin was estimated using the same approach devised for RHB stars and we expect to find $\approx 49 \pm 7$ field stars in the CMD box adopted to define bright RGs. Data listed in Table 1 show that the number of RGs steadily decreases from 444 for $r \leq r_o$ to 232 for $r_p \leq r \leq r_t$. The total number of RGs we detected is 40% larger than the number found by Castellani et al. (2006). Interestingly enough, the $R$ parameter, i.e., the ratio between HB and RG stars brighter than the ZAHB, increases from 1.32 ± 0.08 to 2.76 ± 0.21 (see Table 1). The difference is larger than 5σ and confirms the trend found by Castellani et al. (2006). To further constrain these findings we performed the same RG counts, but using the F814W-band. Data listed in Table 1 show the same
trend for RGs and the difference in the $R$ parameter between the innermost and the outermost radial bin is larger than $4\sigma$. The current evidence indicates a deficiency of bright RGs in the outermost cluster regions.

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