ON THE $\Delta V_{\text{HB}}$ BUMP PARAMETER IN GLOBULAR CLUSTERS

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ABSTRACT

We present new empirical estimates of the $\Delta V_{\text{HB}}$ parameter for 15 Galactic globular clusters (GGCs) using accurate and homogeneous ground-based optical data. Together with similar evaluations available in the literature, we ended up with a sample of 62 GGCs covering a very broad range in metal content ($\approx 2.16$ dex $\leqslant [\text{M/H}] \leqslant -0.58$ dex). Adopting the homogeneous metallicity scale provided either by Kraft & Ivans or by Carretta et al., we found that the observed $\Delta V_{\text{HB}}$ parameters are larger than predicted. In the metal-poor regime ([M/H] $\lesssim -1.7$, $-1.6$ dex) 40% of GCs show discrepancies of $2\sigma (\approx 0.40$ mag) or more. Evolutionary models that account either for $\alpha$- and CNO-enhancement or for helium enhancement do not alleviate the discrepancy between theory and observations. The outcome is the same if we use the new solar heavy-element mixture. The comparison between $\alpha$- and CNO-enhanced evolutionary models and observations in the Carretta et al. metallicity scale also indicates that observed $\Delta V_{\text{HB}}$ parameters, in the metal-rich regime ([M/H] $\gtrsim 0$), might be systematically smaller than predicted.

Key words: globular clusters: general – stars: evolution – stars: horizontal-branch – stars: Population II

Online-only material: color figures

1. INTRODUCTION

Globular clusters (GCs) possess several evolutionary features that show up in the color–magnitude diagram (CMD) and/or in the luminosity function (LF). Along the red giant branch (RGB) there is a well-defined bump in the differential LF and, equivalently, a change in the slope of the cumulative LF. This occurs when the H-burning shell crosses the chemical discontinuity left behind by the deepest penetration of the convective envelope (first dredge-up) at the base of the RGB (Thomas 1967; Iben 1968; Renzini & Fusi Pecci 1988; Castellani et al. 1989). The efficiency of the H-burning shell is affected by the sharp increase in the hydrogen abundance and the stellar luminosity experiences a temporary drop. Stars thus cross the same luminosity range three times, and a bump/overdensity appears in the differential LF of RGB stars.

The RGB bump is interesting because: (1) the luminosity and shape provide robust constraints on the chemical properties inside RG structures and demark the maximum downward penetration of the convective envelope during the first dredge-up (Bergbusch & Vandenberg 2001; Cassisi et al. 2002); and (2) the luminosity peak can also be used to estimate either the cluster metallicity (Desidera et al. 1998) or the cluster distance. However, the bump luminosity is affected by both theoretical (treatment of the convective transport in stellar envelopes) and observational (distance, reddening) uncertainties. To overcome the latter, Fusi Pecci et al. (1990, hereinafter FP90) suggested using the $\Delta V_{\text{HB}} = V(\text{bump}) - V(\text{HB})$ parameter, i.e., the difference in apparent visual magnitude between the RGB bump and the horizontal branch (HB) at the luminosity level of RR Lyrae instability strip. Using new estimates of this parameter for 11 GCs, FP90 found that the observed $\Delta V_{\text{HB}}$ values were 0.4 mag fainter than predicted. This gave rise to a series of theoretical (Alongi et al. 1991; Bono & Castellani 1992; Bergbusch & Vandenberg 2001) and observational (Alves & Sarajedini 1999; Ferraro et al. 1999) investigations.

Cassisi & Salaris (1997) gave a new spin to this problem, finding good agreement between theory and observations once the global metallicity of individual clusters was taken into account. This was confirmed by Zoccali et al. (1999) using a large sample (28) of GCs covering a wide metallicity range.
(−2.1 dex ≤ [Fe/H] ≤ −0.3 dex). The comparison between the evolutionary lifetimes during the crossing of the H–discontinuity and star counts across the RGB bump led also to good agreement between theory and observations (Bono et al. 2001). More recently, Riello et al. (2003, hereinafter R03) found that predicted ΔV_{HB} values agree quite well with observations for cluster ages of 12 ± 4 Gyr. This investigation used a sample of 54 GCs, but only three metal-poor ([M/H] ≤ −1.75 dex) GCs were included. Note that identification of the RGB bump in metal-poor GCs is more difficult since it is brighter than the HB, where evolution along the RGB becomes faster and the stellar sample, consequently, becomes smaller.

Here, we augment the previous observations by investigating ΔV_{HB} in a large sample of GCs with metallicities ranging from −2.43 to −0.70 dex. In particular, we focus our attention on different sources of possible systematic errors, namely, metallicity scale, α-elements, CNO abundances, and helium content.

2. EMPIRICAL AND THEORETICAL FRAMEWORKS

From the database maintained by Stetson (2000), we selected 15 GCs with low reddening (E(B−V) ≤ 0.10; Harris 1996) and a wide range in metallicity (−2.43 ≤ [Fe/H] ≤ −0.70, see data listed in Table 1). The B and V data adopted in this investigation come from original and archival observations which have been collected, reduced, and calibrated by one of us (P.B.S.) in an ongoing effort to provide homogeneous photometry on the Landolt (1992) photometric system for a significant fraction of GCs. More details concerning individual fields can be found at the following URL: http://www4.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/community/STETSON/standards/ or by direct communication with P.B.S.

To find the RGB bump, we represented each RG star detected in the B, V bands by a Gaussian kernel with a σ equal to the photometric uncertainty. The differential RGB LF was formed by summing the individual Gaussians and the position of the bump was estimated by fitting the resulting peak with a Gaussian. Data plotted in Figure 2 show that the photometric error in color, added in quadrature, is on average of the order of 0.01 mag from bright RGs to stars fainter than the main-sequence turn-off (MSTO). Therefore, the uncertainty in the measured position was assumed, as a generous estimate, equal to the sigma of the fitting Gaussian. The fit was performed using an interactive program that performs analytical fits to the main peaks of a given distribution (Calamida et al. 2009). On the basis of the residuals between the RGB LF and the analytical fit, the software allows us to remove/insert new Gaussian components manually.

The HB level for GCs with either an intermediate or a red HB morphology was estimated using the LF of HB stars in the flat region. Specifically, the zero-age horizontal branch (ZAHB) level was estimated at 3σ fainter than the peak of the LF (see the bottom right panel of Figure 1). Note that the 3σ values range from ~0.09 in metal-poor clusters to ~0.18 mag in metal-rich clusters. This approach may be compared to the procedure adopted by Zoccali et al. (1999) and by Riello et al. (2003) for GCs with a red HB morphology (metal-rich). They fit the lower envelope of the HB stellar distribution, and the ZAHB level was fixed at 3σ above the lower envelope. The former approach is less affected by accidental measuring errors, since it relies on the peak of the LF. On the other hand, for Galactic globular clusters (GGCs) with a blue HB morphology (typically metal-poor and metal-intermediate GCs with only a few red HB stars) we used a template cluster with the same metallicity and a well-populated HB. The HB level was estimated by shifting the template cluster in magnitude and in color (Buonanno et al. 1986; Ferraro et al. 1992; Zoccali et al. 1999). The observational errors for the CMDs of Figure 1 are presented in Figure 2.

The uncertainty of ΔV_{HB} was estimated by adding in quadrature the standard errors of the bump and HB luminosities (see Table 1). To increase the sample size we also included the ΔV_{HB} of R03. However, their ΔV_{HB} parameters were based on the F555W band of WFPC2@HST (see their Table 1). We

| ID     | Alias | Δbump  | ΔV_{HB}      | [Fe/H]       |
|--------|-------|--------|--------------|--------------|
| NGC 104 | 47Tuc | 14.50 ± 0.04 | +0.27 ± 0.11 | −0.71 ± 0.05 |
| NGC 288 |      | 15.45 ± 0.02 | +0.02 ± 0.10 | −1.40 ± 0.05 |
| NGC 1261 |     | 16.62 ± 0.05 | −0.22 ± 0.11 | −1.32 ± 0.06 |
| NGC 4590 | M68  | 16.02 ± 0.04 | −0.62 ± 0.11 | −1.12 ± 0.07 |
| NGC 5024 | M53  | 16.58 ± 0.02 | −0.33 ± 0.10 | −1.11 ± 0.07 |
| NGC 5272 | M3   | 15.44 ± 0.03 | −0.42 ± 0.10 | −1.50 ± 0.05 |
| NGC 5904 | M5   | 14.98 ± 0.03 | −0.23 ± 0.10 | −1.38 ± 0.05 |
| NGC 6205 | M13  | 14.73 ± 0.05 | −0.35 ± 0.11 | −1.63 ± 0.04 |
| NGC 6341 | M92  | 14.62 ± 0.02 | −0.60 ± 0.10 | −1.89 ± 0.05 |
| NGC 6362 |      | 15.52 ± 0.02 | +0.05 ± 0.10 | −1.12 ± 0.07 |
| NGC 6723 |      | 15.60 ± 0.02 | −0.01 ± 0.10 | −0.96 ± 0.04 |
| NGC 6752 |      | 13.68 ± 0.05 | −0.03 ± 0.11 | −1.12 ± 0.07 |
| NGC 6809 | M55  | 14.17 ± 0.03 | −0.26 ± 0.10 | −1.80 ± 0.02 |
| NGC 7089 | M2   | 15.82 ± 0.05 | −0.19 ± 0.11 | −1.61 ± 0.04 |
| NGC 7099 | M30  | 14.71 ± 0.05 | −0.45 ± 0.11 | −2.05 ± 0.03 |

Table 1. Iron Abundances and ΔV_{HB} for the 15 GCs in our Sample

Notes.

a Iron abundances by Rutledge et al. (1997, RHS97) in the Zinn & West (1984, ZW84) and in the Carretta & Gratton (1997, CG97) metallicity scale.

b Iron abundances by Carretta et al. (2009, C09).

c Iron abundances by Kraft & Ivans (2003, 2004, KI04).
have nine clusters in common with R03 and we found a mean difference of 0.06 ± 0.03, i.e., a factor of 2 smaller than the typical uncertainty. We applied this shift in magnitude to the R03 estimates; our results are independent of this magnitude correction. For the clusters in common with R03, we adopted our $\Delta V_{\mathrm{HB}}$ values, since the number of RGB stars across the bump region is larger. We ended up with a sample of 62 GCs.

To compare theory and observations we adopted different metallicity scales. (1) The metallicity scale by Carretta et al. (2009, hereinafter C09), based on iron measurements of Fe\textsc{i} lines from intermediate resolution ($R \approx 20,000$) spectra collected with GIRAFFE at the Very Large Telescope (VLT) and from high-resolution spectra collected with UVES at VLT ($R \approx 40,000$). They observed 19 calibrating GGCs and for each GC they collected $\sim 100$ GIRAFFE and $\sim 10$ UVES spectra. The estimated mean uncertainty of these abundances ranges from 0.03 (NGC 1904) to 0.08 (NGC 2808) dex. (2) The metallicity scale by Kraft & Ivans (2003, 2004, hereinafter KI03 and KI04), based on high-resolution spectra ($R \approx 30,000$; Shetrone & Keane 2000) and on MARCS atmosphere models. This scale has two key advantages: (i) iron abundances based on measurements of Fe\textsc{i} lines, which are minimally affected by non-LTE effects (Thevenin & Idiart 1999) and (ii) robust determinations of surface gravity and effective temperature. The accuracy of this scale is on average better than 0.1 dex. (3) Metallicities by Rutledge et al. (1997, hereinafter RHS97), derived from homogeneous and accurate measurements of the calcium triplet, referred to both the Zinn & West (1984, hereinafter ZW84) and the Carretta & Gratton (1997, hereinafter CG97) metallicity scales. The typical precision of these metallicities is 0.10–0.15 dex (KI04). Note that the cluster metallicities provided by ZW84 were based on various diagnostics (G band, Ca\textsc{ii} K, and Mg\textsc{i} lines), and their typical precision is $\sim 0.15$ dex.

To estimate the global metallicity ([M/H]) of individual GCs, we adopted the relation by Salaris et al. (1993) and assumed $[\alpha/Fe] = +0.4$ dex for all GCs. This assumption is based on spectroscopic measurements of $\alpha$-elements in GCs (see Figure 4 in Gratton et al. 2004). The idea of a constant $[\alpha/Fe]$ as a function of the metal content relies only on three metal-rich GCs (NGC 6528, NGC 6553, and Liller 1), while field stars show a steady decrease in $\alpha$-element abundances in the approach to solar chemical composition. However, we adopted a constant $[\alpha/Fe]$ ratio, because field and cluster stars show different abundance patterns (see Section 3). Among our 62 GCs, metallicity estimates are available for 37 objects in RHS97 and 60 in KI04, while the entire sample is included in the C09 metallicity compilation.

To compare theory with observations, we adopted the $\alpha$-enhanced isochrones and ZAHBs available in the BaSTI database. We adopted isochrones that neglect atomic diffusion (Pietrinferni et al. 2006). The global metallicity ranges from $[\mathrm{M}/\mathrm{H}] = -2.27$ to +0.06 dex, the primordial helium content by mass is $Y_p = 0.245$, and the helium-to-metal enrichment ratio, $\Delta Y/\Delta Z$, is 1.4, while the stellar mass of the progenitors (MSTO) ranges from 0.78 $M_\odot$ ([M/H] = $-2.27$) to 0.90 $M_\odot$ ([M/H] = +0.06). Predicted $\Delta V_{\mathrm{HB}}$ values were estimated assuming a GC age of 12 Gyr (VandenBerg et al. 2006).

To estimate the typical uncertainty in the predicted $\Delta V_{\mathrm{HB}}$ values we assumed an uncertainty of 0.1 dex in the heavy-element abundances (Fe, $\alpha$-elements), 0.02 in the helium content by mass ($Y$), and 1 Gyr in the cluster age. Moreover, we also included uncertainties in the input physics used in constructing evolutionary models (Cassisi et al. 1998; Bergbusch & VandenBerg 2001).

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\textsuperscript{15} Evolutionary models can be downloaded from http://www.oa-teramo.inaf.it/BASTI.
Figure 3. $\Delta V_{\text{HB}}$ bump as a function of the global metallicity $[\text{M/}\text{H}]$. From top to bottom the same data are plotted using different metallicity scales: Rutledge et al. (1997, RHS97) in the Zinn & West (1984, ZW84) scale; RHS97 in the Carretta & Gratton (1997, CG97) scale; Kraft & Evans (2004, KI04); C09. The number of GCs in each panel is also labeled ($N_c$). The circles display $\Delta V_{\text{HB}}$ parameters from Riello et al. (2003), while the squares show current estimates. The red line shows predictions (BaSTI) at fixed age (12 Gyr) for $[\text{M/}\text{H}]$ ≲ −1.5. The error bar plotted in the right corner of the top panel shows the quadrature sum of theoretical and empirical uncertainties. The GCs with difference from theory larger than $\sigma$ and $3\sigma$ are plotted in green and in blue.

(A color version of this figure is available in the online journal.)

3. COMPARISON WITH $\alpha$- AND CNO-ENHANCED MODELS

Figure 3 shows the comparison between empirical and predicted $\Delta V_{\text{HB}}$ bump values in the four different metallicity scales. The model shows that the observed $\Delta V_{\text{HB}}$ bump values of metal-poor and metal-intermediate GCs are systematically larger than predicted. This discrepancy does not depend on the adopted metallicity scale and becomes strongest in metal-poor ($[\text{M/}\text{H}] < -1.5$) GCs. To be more quantitative we calculated for each GC the quadrature sum of theoretical and empirical uncertainties (see Table 1 and Figure 3). We found that the GCs with a discrepancy larger than $2\sigma$ (green symbols in Figure 3) are two, four, and five for the RHS97[ZW84], the KI04, and the C09 metallicity scale. It is worth mentioning that the difference between theory and observations is $\approx 0.40$ mag. We also found that one GC in KI04 shows a discrepancy larger than $3\sigma$ ($\approx 0.60$ mag). This suggests that metallicities based either on KI04 or on C09 scale show a very similar behavior when compared with observations. However, the bottom panel shows that several metal-rich ($[\text{M/}\text{H}] \approx -0.5$ dex) GCs in the C09 metallicity scale are located below the predicted loci. Note that the possible evolutionary effects in the HB phase would imply an increase (more positive) in the value of the $\Delta V_{\text{HB}}$ bump. Figure 3 indicates that—if we trust the KI04 and C09 metallicity scales—approximately 40% of the metal-poor ($[\text{M/}\text{H}] < -1.7, -1.6$ dex) GCs show a discrepancy with theory that is at least at a $2\sigma$ level. Such a discrepancy can hardly be explained as a spread in cluster age: the age derivative of the $\Delta V_{\text{HB}}$ bump parameter is $\approx 0.03$ mag per Gyr over the entire metallicity range (see, e.g., Cassisi & Salaris 1997; Zoccali et al. 1999), and an age spread of order 10 Gyr seems out of the question. Moreover, changes in mixing-length efficiency have little effect on the luminosity of the RGB bump: a change of ±0.1 in $\alpha$ causes a variation of $\sim 0.03$ mag in the $\Delta V_{\text{HB}}$ bump parameter (Cassisi & Salaris 1997). The comparison between predicted and empirical cluster RGBs does not support larger variations in the $\alpha$ parameter. The anonymous referee raised the problem that we are using a sample of $\Delta V_{\text{HB}}$ bump parameters that are based on two different methods to estimate the ZAHB luminosity. According to the referee there is a big possibility of systematic errors in the ZAHB determinations. However, some circumstantial evidence argues against this working hypothesis.

1. The photometric precision of the current data and of the Hubble Space Telescope (HST) data adopted by Riello et al. at the ZAHB level is better than 0.010–0.015 mag over the entire cluster sample. We have nine GCs in common with Riello et al. that cover the entire metallicity range and the difference in the estimated $\Delta V_{\text{HB}}$ bump parameters is smaller than 0.1 mag.

2. The method we adopted to estimate the ZAHB luminosity ($\sigma$ fainter than the peak of HB LF) might be prone to underestimate the real ZAHB level. However, a less conservative estimate would imply brighter ZAHBs, and in turn larger (more positive) $\Delta V_{\text{HB}}$ bump parameter and therefore a larger discrepancy between theory and observations.

3. We estimated the $\Delta V_{\text{HB}}$ bump parameter for a good fraction (six out of eleven) of metal-poor ($[\text{M/}\text{H}] \lesssim -1.7, -1.6$ dex) GCs. If we do not include the GCs measured by Riello et al. the discrepancy between theory and observations, in this metallicity range, becomes larger.

4. The majority (nine out of twelve) of the $\Delta V_{\text{HB}}$ bump parameters of metal-rich ($[\text{M/}\text{H}] \gtrsim -0.3$ dex) GCs have been estimated by Riello et al.

5. To overcome subtle uncertainties in empirical estimates and theoretical predictions, we focus our attention on discrepancies at the level of several tenths of a magnitude.

Finally, we also compared current estimates of $V_{\text{ZAHB}}$ with similar estimates provided by Ferraro et al. (1999) to test whether our approach may also introduce a zero-point shift or a systematic trend with metallicity. The quoted authors, to estimate $V_{\text{ZAHB}}$ in a large sample of GGCs with nonhomogeneous photometry, applied a metallicity-dependent correction to $V_{\text{HB}}$ ranging from 0.06 to 0.16 mag. We have 10 GGCs in common with Ferraro et al. and data plotted in Figure 4 show no evidence of a trend with metallicity and the two different sets of $V_{\text{ZAHB}}$ estimates agree within $1\sigma$.

There are several culprits that can explain the difference between current predictions and those provided by Cassisi & Salaris (1997). Their primordial He-content was $Y = 0.23$ while ours is $Y = 0.245$, and the estimated cluster age has been decreased from 15 to 12 Gyr. The input physics (opacities, equation of state) was also changed, and they adopted a scaled-solar heavy-element mix rather than an $\alpha$-enhanced one.
However, the difference between the old and the new scaled-solar $\Delta V_{\text{HB}}^\text{bump}$ parameter for $[\text{M}/\text{H}] = -1.79$ and $t = 15$ Gyr is small ($-0.65$ versus $-0.60$). The difference with the new $\alpha$-enhanced $\Delta V_{\text{HB}}^\text{bump}$ parameter, for the same chemical composition and an age of 12 Gyr, is also modest ($-0.65$ versus $-0.75$). Given the limited changes between the current and previous predictions, the discrepancy between theory and observations in the metal-poor tail is confirmed and reinforced by the inclusion of new GCs in this metallicity regime.

We note in passing that theoretical models indicate that the RGB bump luminosity is marginally affected by plausible assumptions concerning the smoothing of the chemical discontinuity (Bono & Castellani 1992). Following a different approach, Alongi et al. (1991) found that the inclusion of nonlocal overshoot at the base of the convective envelope causes, in low-mass RGB stars, an increase of 0.4 V mag in the location of the RGB bump. However, this systematic shift minimally depends on the chemical composition and applies to both metal-poor and metal-rich stellar structures.

Spectroscopic measurements suggest variations in the abundance pattern in GCs on a star-by-star basis. Together with changes in the relative abundances of CNO elements, well-defined anti-correlations have been found between O and Na and between Mg and Al (Gratton et al. 2004, and references therein). This applies not only to evolved and unevolved cluster stars (Briley et al. 1996; Cohen & Meléndez 2005) but also to RG stars characterized by different thicknesses of the convective envelope (Pietrinferni et al. 2009). This solid result and the recent evidence that field halo stars do not show, at fixed iron content, similar changes in (O, Na, Mg, Al) suggest the occurrence of an intra-cluster pollution mechanism (Denissenkov & Weiss 2004; Ventura & D’Antona 2005; Salaris et al. 2006).

Moreover, Yong et al. (2009) found that the $[\text{C} + \text{N} + \text{O}/\text{Fe}]$ abundance ratio changes by a factor of 4 (0.6 dex) among bright RGs in the GC NGC 1851. This is consistent with the scenario suggested by Cassisi et al. (2008) to explain the two subgiant branches detected in this cluster (Milone et al. 2008) as a difference in the mixture of C + N + O elements.

To investigate the discrepancy between theory and observations of $\Delta V_{\text{HB}}^\text{bump}$, we also considered cluster isochrones and ZAHBs constructed assuming CNO–Na abundance anti-correlations (Pietrinferni et al. 2009). The mixture adopted in these evolutionary models includes a sum in CNO abundances that is a factor of 2 larger than in a canonical $\alpha$-enhanced mixture and within the observed range of GC anti-correlations (Salaris et al. 2006). Predictions by Pietrinferni et al. (2009) are available for stars with metallicities from $[\text{M}/\text{H}] = -1.27$ ($M_{\text{MSTO}} = 0.79 M_\odot$) to $[\text{M}/\text{H}] = -0.07$ ($M_{\text{MSTO}} = 0.83 M_\odot$) dex. To constrain the predictions in the metal-poor regime, we used an updated version of the FRANEC evolutionary code (Caruolo et al. 2004; Degl’Innocenti et al. 2008) to compute stellar isochrones and ZAHBs for $[\text{M}/\text{H}] = -1.77$ ([Fe/H] $= -2.32$, $[\alpha/\text{Fe}] = 0.3$, $Y = 0.246$, $M_{\text{MSTO}} = 0.78 M_\odot$) accounting for both $\alpha$- and CNO-enhancement. These models include atomic diffusion, which causes a decrease in the inferred cluster age of ~1 Gyr (Bahcall & Pinsonneault 1995; Castellani et al. 1997). Therefore, we estimated the $\Delta V_{\text{HB}}^\text{bump}$ parameter for a cluster age of 11 Gyr and the blue asterisk marks its position in Figure 5. A more detailed discussion concerning the input...
physics of these models will be addressed in a forthcoming investigation (Di Cecco et al. 2010, in preparation). Note that current predictions for CNO-enhanced models do not cover the metallicity range $-1.77 < [\text{M}/\text{H}] < -1.27$ (see the dashed line in Figure 5). However, the linear interpolation (see the dashed line in Figure 5) is supported by the smooth change showed by more metal-rich structures (Pietrinferni et al. 2009). To compare theory and observations, the global metallicity of GCs was estimated using the Salaris et al. (1993) relation with $[\alpha/\text{Fe}] = 0.4$ and $[\text{CNO}/\text{Fe}] = 0.3$. The comparison indicates that $\alpha$- and CNO-enhanced predictions display a similar discrepancy with empirical estimates in the KL04 (three GCs with a difference larger than $2\sigma$ and one with a difference larger than $3\sigma$) and C09 (four GCs with a difference larger than $2\sigma$ and one with a difference larger than $3\sigma$) metallicity scale (see the green lines in Figure 5). The difference is mainly due to the fact that the RGB bump is more sensitive to an increase in CNO abundances than the ZAHB (see Figures 1 and 3 in Salaris et al. 2008). On the other hand, the bottom panel of Figure 5 shows that, if we adopt the C09 metallicity scale, a group of six GCs in the metal-rich regime ($[\text{M}/\text{H}] > 0.0$) shows systematically smaller (more negative) $\Delta V_{\text{HB}}$ values than predicted. Current predictions do not cover this metallicity range and we linearly extrapolated the trend from more metal-poor structures. Note that Figure 5 shows only the KL04 and the C09 metallicity scales because they include the largest fraction of GCs in our sample. The main outcome of the above comparison is that the observed $\Delta V_{\text{HB}}$ parameters in the metal-poor regime are systematically larger (more positive), independent of the metallicity scale, than predicted by $\alpha$- and CNO-enhanced models. A similar discrepancy, but with observed $\Delta V_{\text{HB}}$ parameters systematically smaller than predicted, might also be present in the metal-rich tail ($[\text{M}/\text{H}] > 0.0$), if we adopt the C09 metallicity scale.

The anonymous referee suggested a test to constrain the fraction of CNO-enhanced stars that could be identified as a secondary RGB bump. Accordingly, we computed a series of synthetic CMDs assuming a metal-poor chemical composition ($Y = 0.246$, $[\text{Fe}/\text{H}] = -2.32$, $[\alpha/\text{Fe}] = 0.3$, Pisa evolutionary code) and a cluster age of 11 Gyr. Together with this canonical stellar population we also included different fractions of a CNO-enhanced stellar component. We assumed for the CNO-enhanced population two different ages, namely, 11 and 10 Gyr (see the left and right panels of Figure 6). Moreover, we have made our best efforts to match the synthetic CMD to the observed CMD of M92. In particular, we randomly distributed the same number of stars (2500; $V \geq 16$ mag) along the predicted RGB to mimic the Poisson uncertainties properly and accounting for photometric errors ($\sigma_B, \sigma_V \leq 0.015$ mag). Figure 6 shows the predicted LFs with CNO-enhanced fractions from 20% (top) to 50% (bottom). To define the RGB bump, we adopted the same procedure as for observed GCs. Data plotted on the left column (coeval populations) indicate that CNO-enhanced stars show up as a secondary RGB bump when its fraction is equal to or larger than 30%. Note that the two peaks differ in magnitude by 0.1 mag, i.e., an order of magnitude larger than the typical photometric error. On the other hand, if we assume an age difference of 1 Gyr between the canonical and the CNO-enhanced population (right column) the secondary population shows up as a second RGB bump only when its fraction becomes of the order of 40%–50%. This is due to the fact that the effects of a decrease in cluster age and of an increase in the global metallicity almost cancel out across the RGB bump. The magnitude difference between the peaks is 0.08 mag. This indicates that RGB bump is not a good indicator of the presence of a sub-population that is both CNO-enhanced and younger relative to the main population.

### 4. COMPARISON WITH He-ENHANCED MODELS

Recently, accurate and deep photometry has revealed multiple stellar populations in several massive GCs. Together with the highly complex system of the Centauri (Anderson 2002; Bedin et al. 2004) multiple stellar sequences have been detected in GCs covering a broad range of metal content: NGC 2808 (D’Antona et al. 2005; Pietro et al. 2007), M54 (Siegel et al. 2007), NGC 1851 (Milone et al. 2008), and M4 (Marino et al. 2008). Some of these multiple sequences ($\omega$ Cen, NGC 2808) might be explained with a He-enhanced stellar population (Norris 2004; D’Antona et al. 2005; D’Antona & Caloi 2008; Pietro et al. 2007).

To evaluate the impact that the He-content has on $\Delta V_{\text{HB}}$ we also considered evolutionary models assuming higher helium abundances. The top panels of Figure 7 show the comparison, at fixed cluster age (12 Gyr), between observed and predicted (BaSTI) $\Delta V_{\text{HB}}$ parameters. Together with the canonical $\alpha$-enhanced models (red line) the He-enhanced models are plotted with a blue ($Y = 0.30$; $M_{\text{MSTO}} = 0.72 M_{\odot}$ at $[\text{M}/\text{H}] = -1.27$ and $M_{\text{MSTO}} = 0.78 M_{\odot}$ at $[\text{M}/\text{H}] = -0.35$) and a green ($Y = 0.35$; $M_{\text{MSTO}} = 0.68 M_{\odot}$ at $[\text{M}/\text{H}] = -0.66$ and $M_{\text{MSTO}} = 0.72 M_{\odot}$ at $[\text{M}/\text{H}] = -0.35$) line, respectively.

The He-enhanced models predict larger $\Delta V_{\text{HB}}$ parameters when compared with canonical models. The difference is most evident in the metal-rich tail; it is negligible in the metal-intermediate regime because an increase in helium content— at fixed cluster age—gives brighter ZAHBs and brighter RGB bumps. Note that the He-enhanced models do not exist in the metal-poor regime, since these models experience either no first dredge-up, or only a mild one. The RGB bump vanishes together with the chemical discontinuity in the envelope.

Finally, we also tested the impact of simultaneous changes in both cluster age and helium content. The bottom panels of Figure 7 show the comparison between canonical and He-enhanced models for a cluster age of 10 Gyr ($Y = 0.245$, $M_{\text{MSTO}} = 0.82 M_{\odot}$ for $[\text{M}/\text{H}] = -2.27$ and $M_{\text{MSTO}} = 0.93 M_{\odot}$ for $[\text{M}/\text{H}] = +0.06$; $Y = 0.30$, $M_{\text{MSTO}} = 0.75 M_{\odot}$ for $[\text{M}/\text{H}] = -1.79$ and $M_{\text{MSTO}} = 0.81 M_{\odot}$ for $[\text{M}/\text{H}] = -0.35$; $Y = 0.35$, $M_{\text{MSTO}} = 0.69 M_{\odot}$ for $[\text{M}/\text{H}] = -0.96$ and $M_{\text{MSTO}} = 0.74 M_{\odot}$ for $[\text{M}/\text{H}] = -0.35$). Once again the predicted $\Delta V_{\text{HB}}$ values are systematically smaller than observed, regardless of the metallicity scale. The decrease in cluster age expands the range in metal content within which the He-enhanced models display the RGB bump. However, in the metal-intermediate regime ($-1.77 \lesssim [\text{M}/\text{H}] \lesssim -0.8$) the difference between canonical and He-enhanced ($Y = 0.30$) models is negligible. This is because the He-enhancement causes similar changes in $V_{\text{HB}}$ and $V_{\text{Bump}}$ that cancel out in the difference.

The anonymous referee suggested a test to constrain the impact of a sub-population of He-enhanced stars on the shape and width of the RGB bump. Accordingly, we computed several series of evolutionary models (using the Teramo evolutionary code) at fixed global metallicity, but steadily increasing the initial He abundance from the canonical value ($Y \sim 0.25$) to the disappearance of the bump (see Table 2). Figure 8 shows the predicted width in visual magnitude between the faintest and the brightest point attained by the RGB bump for metal-poor (dashed-dotted line), metal-intermediate (dashed line), and...
metal-rich (solid line) stellar structures constructed assuming different helium contents and fixed cluster age. This figure shows that the width in magnitude increases by \( \approx \) a factor of 5 when moving from metal-poor to metal-rich structures. In metal-poor structures an increase in helium of \( \sim 10\% \) causes the disappearance of the bump, since its width becomes smaller than one hundredth of a magnitude. The same result occurs in metal-intermediate and metal-rich structures, but the required increase in helium content is of the order of 30\%–35\%. The disappearance of the RGB bump is a consequence of the decrease in the greatest depth of the convective envelope, and in turn in the reduced amount of nuclear processed material dredged-up into the outermost regions (Salaris & Cassisi 2008). This also means that an increase in helium content has a stronger impact on the width of the RGB bump of metal-poor structures than of the metal-rich ones. In order to be more quantitative on this key dependence we also computed, for the same structures, the increase in surface helium abundance after the first dredge-up (see Column 6 in Table 2). We found that in a metal-poor structure with \( Y = 0.35 \) the amount of extra helium, i.e., the amount of helium dredged-up into the surface layers by the sinking of the convective envelope, decreases by a factor of 2 when compared with structures constructed assuming a canonical helium content. The same outcome applies for metal-intermediate and metal-rich structures, but only for \( Y = 0.40 \).

5. DISCUSSION

New electron-conduction opacities provided by Cassisi et al. (2007) have a negligible effect on the luminosity of the RGB bump, but affect the size of the helium core, and in turn the HB luminosity. The helium core mass of the new models decreases,
The current discrepancy between theory and observations is little affected by the new solar heavy-element mixture provided by Asplund et al. (2005, hereinafter A05). The new mixture has a twofold impact on GC metallicities, since it affects both the iron content ([Fe/H]) and the relation between the iron and the heavy-element abundance adopted in evolutionary computations. To quantify the difference between the old and new solar mixtures on the iron measurements we consider the GC M92. According to KI04 this GC has an iron content of [Fe/H] = −2.32 dex, if we adopt the new solar iron abundance log e_{Fe} = 7.45 (A05), since [Fe/H]_{A05} = [Fe/H]_{GN93} + 0.06 dex. The new solar mixture by A05 gives global metallicities, Z, that at fixed iron content are approximately 30% lower than those based on the GN93 solar mixture, since (Z/X)_{A05}/(Z/X)_{GN93} ≈ 0.7. Given the above differences, the global metallicity of M92, assuming an α-enhancement of +0.4, changes from Z = 1.51 × 10^{-4} (GN93) to Z = 1.19 × 10^{-4} (A05).

![Figure 7](image.png)

**Figure 7.** Same as Figure 3, but for two different metallicity scales: Kraft & Ivanov (2004, KI04, left) and Carretta et al. (2009, C09, right). Top: the lines display predictions (BaSTI) at fixed cluster age (12 Gyr), α-enhanced chemical composition, and different helium contents: Y = 0.245 (red), Y = 0.30 (blue), and Y = 0.35 (green). Bottom: same as the top, but the predictions refer to cluster isochrones of 10 Gyr.

(A color version of this figure is available in the online journal.)

| [M/H] | Z   | Y   | M_{pl}/M_⊙ | ΔV_{HB} |
|-------|-----|-----|------------|---------|
| −1.79 | 0.00030 | 0.246 | 0.8000 | 0.009 |
| −1.79 | 0.00028 | 0.300 | 0.7300 | 0.007 |
| −1.79 | 0.00026 | 0.350 | 0.6600 | 0.005 |
| −1.79 | 0.00024 | 0.400 | 0.6000 | 0.003 |
| −0.96 | 0.00200 | 0.248 | 0.8000 | 0.014 |
| −0.96 | 0.00180 | 0.300 | 0.7600 | 0.012 |
| −0.96 | 0.00170 | 0.350 | 0.7000 | 0.009 |
| −0.96 | 0.00160 | 0.400 | 0.6600 | 0.006 |
| −0.35 | 0.00800 | 0.256 | 0.9000 | 0.020 |
| −0.35 | 0.00760 | 0.300 | 0.8000 | 0.016 |
| −0.35 | 0.00700 | 0.350 | 0.7500 | 0.013 |
| −0.35 | 0.06500 | 0.400 | 0.6700 | 0.009 |

Notes.

- Stellar mass of the progenitor at the tip of the RGB.
- Surface extra helium after the first dredge-up.
6. SUMMARY AND FINAL REMARKS

We estimated the $\Delta V_{\text{HB}}^{\text{bump}}$ parameter for 15 GGCs using accurate and homogeneous optical databases. Combining the new empirical evaluations with similar estimates provided by Riello et al. (2003), we ended up with a sample of 62 GGCs covering a very broad range in metal content ($-2.16 \, \text{dex} \leq [\text{M/H}] \leq -0.58 \, \text{dex}$) and structural parameters. The comparison between theory and observations produced the following findings.

1. The observed $\Delta V_{\text{HB}}^{\text{bump}}$ parameters, using the homogeneous metallicity scales for GGCs provided by Kraft & Ivans (2004) and by Carretta et al. (2009), are larger than the predicted ones. In the metal-poor regime ($[\text{M/H}] \lesssim -1.7$, $-1.6 \, \text{dex}$) 40% of GCs show discrepancies of $2\sigma$ ($\approx 0.40$ mag) or more. Evolutionary models that include either $\alpha$- and CNO-enhancement or helium enhancement do not alleviate the discrepancy between theory and observations.

2. The above discrepancy between theory and observations is not affected by the new solar heavy-element mixture.

3. The comparison between $\alpha$- and CNO-enhanced evolutionary models and observations in the Carretta et al. metallicity scale also indicates that observed $\Delta V_{\text{HB}}^{\text{bump}}$ parameters, in the metal-rich regime ($[\text{M/H}] \geq 0$), might be systematically smaller than predicted.

4. Evolutionary models predict, as expected, a strong dependence of the RGB bump on the helium content. Current predictions indicate that an increase in helium of $\sim 10\%$ causes the disappearance of the RGB bump in metal-poor structures. The outcome is the same in metal-intermediate and in metal-rich structures, but the required increase in helium content is of the order of $30\%$–$35\%$.

In this investigation, we assumed a constant CNO-enhancement over the entire metallicity range. However, spectroscopic evidence indicates that the CN strength is correlated with Na, Al, and Mg in metal-poor, with Na and Al in metal-intermediate and with only Na in metal-rich GCs (Smith & Wirth 1991; Gratton et al. 2004). This implies that the CNO-enhancement might depend on the metal abundance (Cottrell & Da Costa 1981).

More detailed investigations concerning the input physics adopted in the computation of low-mass evolutionary models is required before we can reach a firm conclusion. This also applies to the metallicity scale, and in particular to the occurrence of possible systematic errors when moving from very metal-poor to metal-rich GCs.

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