

On the magnitude difference between the main sequence turn off and the red giant branch bump in Galactic globular clusters

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ABSTRACT

We present new measurements of the magnitude of the main sequence turn off and the red giant branch bump in the luminosity function of a sample of Galactic globular clusters with updated estimates of [Fe/H] and [α /Fe], employing photometric data collected with the Advanced Camera for Survey on board the HST. We compare measured and predicted values of the magnitude difference between these two features, a rarely employed diagnostic of the internal structure of low-mass stars at the beginning of their red giant evolution. Our analysis discloses a clear discrepancy between theory and observations, the theoretical red giant branch bump magnitudes being too bright by on average ~ 0.2 mag. This corroborates results from the more widely studied magnitude difference between horizontal branch and red giant bump, avoiding the well known problems associated to the determination of the horizontal branch level from colour magnitude diagrams, and to uncertainties in the luminosity of horizontal branch stellar models. We briefly discuss several potential solutions of this discrepancy.

Key words. stars: evolution – stars: Population II – Galaxy: globular clusters: general

1. Introduction

Several features of colour-magnitude diagrams (CMDs) and luminosity functions (LFs) of Galactic Globular Clusters (GCs) can be employed to test the accuracy of low-mass, metal-poor stellar models (see, e.g. Renzini & Fusi Pecci 1988). The bump appearing in the GC Red Giant Branch (RGB) LF is one of these important benchmarks. It is produced by the encounter of the H-burning shell with the H-abundance discontinuity left over by the outer convection at its maximum depth (Thomas 1967; Iben 1968) reached during the first dredge-up. The sharp increase of the H-abundance **causes a sudden decrease of the mean molecular weight (μ), that affects the efficiency of the H-burning shell, proportional to a high power of μ (see Kippenhahn & Weigert 1994; Salaris & Cassisi 2005). This occurrence causes a temporary drop of the surface luminosity, before it starts to increase again. As a consequence, a low-mass RGB star crosses the same luminosity interval three times, and a bump (over-density) appears in the RGB differential LF (star counts per magnitude bin) of GCs (for a detailed discussion we refer to Salaris et al. 2002). Given that the RGB-bump brightness depends on the maximum depth attained by the convective envelope, and the chemical profile above the advancing H-burning shell, the comparison between predicted and observed luminosity of the RGB-bump, provides valuable information about the**

internal structure of low-mass stars at the beginning of their RGB evolution.

Since its first detection in the LF of NGC104 (47Tuc – King et al. 1985) the RGB bump has been the subject of several theoretical and observational investigations (Fusi Pecci et al. 1990; Cassisi & Salaris 1997; Alves & Sarajedini 1999; Zoccali et al. 1999; Bono et al. 2001; Riello et al. 2003; Bjork & Chaboyer 2006; Di Cecco et al. 2010). Thanks to these works, we have now accurate measurements of its brightness in many GCs as well as in Local Group dwarf galaxies (see Monelli et al. 2010, and references therein).

The parameter routinely adopted to compare observations with theory is the quantity $\Delta V_{HB}^{Bump} = V_{Bump} - V_{HB}$, that is, the V-magnitude (or bandpasses similar to Johnson V) difference between the RGB-bump and the horizontal branch (HB) at the RR Lyrae instability strip level (Fusi Pecci et al. 1990; Cassisi & Salaris 1997). This has the advantage of being formally independent of distance and reddening, and not affected by any uncertainty in the zero point of the photometry. The most recent comparisons between ΔV_{HB}^{Bump} models and observations (see, e.g., Fig. 10 in Di Cecco et al. 2010) seem to confirm a discrepancy (at the level of ~ 0.20 mag or possibly more) for GCs with total metallicity [M/H] below ~ -1.5 , in the sense that the predicted RGB-bump luminosity is too high. The quantitative estimate of the discrepancy depends on the adopted metallicity

scale. At the upper end of the GC metallicity range, the existence of a discrepancy depends on the adopted metallicity scale.

One drawback of using ΔV_{HB}^{Bump} as diagnostic of the RGB-bump luminosity, is that uncertainties in the placement of the observed HB level for GCs with blue HB morphologies, and in theoretical predictions of the HB luminosity (i.e., due to uncertainties in the calculations of the He-core mass at the He-flash, see e.g. Cassisi 2010), hamper the interpretation of discrepancies between theory and observations.

An alternative avenue explored in this paper is offered by measuring the magnitude difference between the Main Sequence (MS) Turn-Off (TO) and the RGB-bump brightness $\Delta V_{TO}^{Bump} = V_{TO} - V_{bump}$, that bypasses the HB. Observationally, an accurate estimate of the TO brightness requires both very high quality photometric datasets, and a detailed analysis of the uncertainty associated with the presence of binary stars. To the best of our knowledge, so far only Caputo & Cassisi (2002) and Meissner & Weiss (2006) have studied the ΔV_{TO}^{Bump} parameter. Caputo & Cassisi (2002) used ΔV_{TO}^{Bump} in combination with $\Delta V_{HB}^{TO} = V_{TO} - V_{HB}$ to investigate the metallicity scale of a large sample of galactic GCs, but did not attempt to assess the level of agreement between predicted and observed ΔV_{TO}^{Bump} values. More recently, Meissner & Weiss (2006) used the ΔV_{TO}^{Bump} together with other CMD age indicators, to check their mutual self-consistency. As a result, they found that the GC ages estimated from ΔV_{TO}^{Bump} were younger by about 2 Gyr, in comparison with estimates based on the ΔV_{HB}^{TO} parameter. This occurrence was interpreted as an evidence that stellar models predict a too bright RGB-bump, by ~ 0.2 - 0.3 mag.

We wish to reanalyze this issue employing new, accurate photometry of a large sample of GCs, that enabled us to determine both TO and RGB-bump magnitudes for 12 GCs, covering a large metallicity range. Our methodological approach is the following. We have first determined the apparent magnitudes of both TO and RGB-bump in our GC sample, and employed the cluster relative distances from a theoretical MS-fitting technique. As a second step, we have estimated individual cluster ages from the TO absolute magnitudes, obtained assuming the empirical MS-fitting distance to NGC6752 by Gratton et al. (2003) as zero point of our relative distance scale. Another set of ages for each cluster is then determined from their observed ΔV_{TO}^{Bump} , and compared with the TO ages. The outcome of this comparison constrains the level of agreement between predicted and observed RGB-bump luminosity, independently of the HB.

The plan of this paper is as follows: section 2 presents briefly the observational dataset and the theoretical models adopted in our analysis; estimates and comparisons of TO and ΔV_{TO}^{Bump} ages are described in section 3, followed by a final discussion.

2. Observational and theoretical framework

We have employed a subsample of F606W and F814W photometries from the ACS GC Survey Treasury Project (Sarajedini et al. 2007), and made use of the $\Delta M_{F606W}^{TO-Bump}$ parameter, that is the counterpart of ΔV_{TO}^{Bump} in the F606W filter. Details on the observations and data reduction, have been already discussed in Sarajedini et al. (2007) and Anderson et al. (2008).

This database has been collected mainly for the aim of investigating relative and absolute GCs ages, and the initial mass function of GC stars. The observational strategy was optimized to obtain accurate photometry of the faint portion of the CMD,

and for many clusters the bright RGB photometry is saturated. In other clusters - belonging mainly to the metal poor tail of the GC metallicity distribution - there are so few RGB stars, that the RGB-bump detection is impossible. As a consequence, the number of GCs with measurements of $\Delta M_{F606W}^{TO-Bump}$ is reduced compared to the total number of objects in the original database (64 clusters). In addition, we chose to restrict our analysis to those globulars with recent (re)determinations of both [Fe/H] (Carretta et al. 2009) and $[\alpha/Fe]$ (Carretta et al. 2010a). More in detail, the values of [Fe/H] are obtained from Table A.1 in Carretta et al. (2009), that displays [Fe/H] estimates for 95 GCs, obtained transforming (and averaging) previous determinations onto the homogeneous scale set by high-resolution spectroscopic measurements on 19 clusters, reported in Table 1 of the same paper. This metallicity scale turns out to be very close to the Zinn & West (1984) estimates. The errors displayed in the same table (that represent the 1σ rms with respect to the metallicity scale set by the high-resolution spectroscopy) are added in quadrature to the average systematic errors in the high resolution estimates of the 19 reference clusters (reported also in Table 1 of the same paper). As for $[\alpha/Fe]$, we assign a typical 0.10 dex uncertainty.

Due to these additional constraints on the metallicity estimates, our sample is reduced to 11 objects, to which we added the NGC6341 (M92), using HST archive data (program 9453, PI T. Brown). For this latter cluster three images in each band were used, with exposure times of 0.5, 5, and 90 s in the F606W band, and 0.5, 6, and 100 s in F814W. The photometry has been reduced with the DAOPHOT/ALLFRAME package (Stetson 1994), and calibrated to the VEGAMAG system following Sirianni et al. (2005). With the inclusion of M92 we are able to cover approximately the whole metallicity range of Galactic GCs.

Measurements of the apparent TO magnitude and associated uncertainties are from Marín-Franch et al. (2009). In brief, these authors employed a MS-fitting technique to determine the relative distance moduli between the reference cluster NGC6752 and all other clusters in our sample. We adopt here a zero point for these relative distances set by the empirical MS-fitting distance to NGC6752 determined by Gratton et al. (2003)¹. The final errors on the absolute magnitudes M_{F606W}^{TO} reported in Table 1 have been obtained by adding in quadrature the errors on the determination of the apparent magnitudes, errors on the relative cluster distances (Marín-Franch et al. 2009), and the error on NGC6752 distance (Gratton et al. 2003). As for the determination of the RGB-bump level, we have employed the following method, illustrated in Fig. 1 for the case of NGC 104. For each cluster, the LF around the bump region has been determined using a bin size equal to 0.1 mag. A linear fit (see right panel of Fig. 1) is then performed around the bump – excluding the bump feature – to obtain what we denote as the LF ‘continuum’ (marked as a solid black line in the right panel of Fig. 1). Finally, the apparent magnitude of the bump (dotted line) is determined at the maximum of the continuum-subtracted LF, and its uncertainty is computed as $\sigma / \sqrt{N_{stars} - 1}$, with N_{stars} and σ denoting the number of bump stars and their standard deviation around the bump luminosity, respectively. Results of these measurements as

¹ The empirical MS-fitting distance to NGC6752 derived in Gratton et al. (2003) was obtained by fitting the observed globular cluster mean locus to the colour magnitude diagram location of local subdwarfs with the same [M/H] of the cluster. Although both [Fe/H] and $[\alpha/Fe]$ values employed by Gratton et al. (2003) are different from the values reported in Table 1 for this cluster, the total metallicity [M/H] turns out to be same within 0.01 dex.

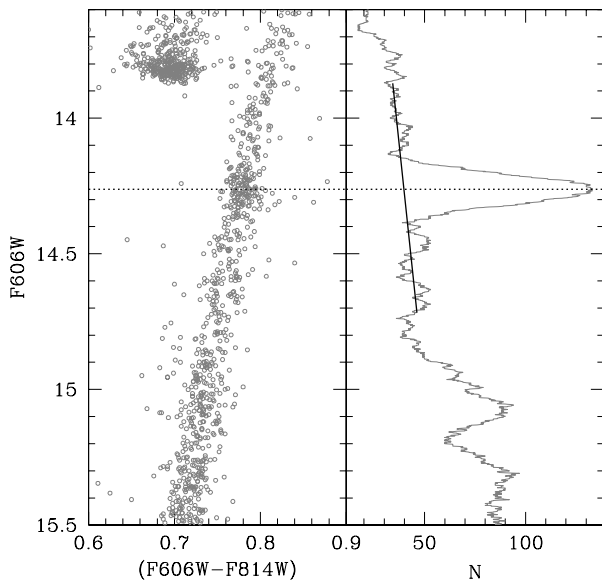


Fig. 1. *Left panel:* CMD of NGC 104. *Right panel:* the LF around the bump region. The solid line shows the continuum used for the bump determination (see text for more details), while the dotted line marks the bump location.

well as $[\text{Fe}/\text{H}]$ spectroscopic estimates and the global metallicity $[\text{M}/\text{H}]$ obtained from the measurements of $[\text{Fe}/\text{H}]$ and $[\alpha/\text{Fe}]$ are reported in Table 1.

Our theoretical analysis makes use of the α -enhanced BaSTI² stellar model library (Pietrinferni et al. 2006) that employ transformations to the ACS/HST photometric system by Bedin et al. (2005). From this extended set of isochrones we have obtained the theoretical estimates of the TO, RGB-bump brightness, and $\Delta M_{F606W}^{\text{TO-Bump}}$ as a function of age and $[\text{M}/\text{H}]$, that are displayed in Fig. 2³.

It is interesting to investigate the sensitivity of the $\Delta M_{F606W}^{\text{TO-Bump}}$ parameter to the cluster age t , in comparison with $\Delta M_{F606W}^{\text{HB-Bump}}$, i.e. the equivalent of the traditional $\Delta V_{\text{HB}}^{\text{Bump}}$. In the age range typical of GCs, the HB is practically unaffected by the exact value of t , while the RGB-bump becomes fainter with increasing t . As a result $\Delta M_{F606W}^{\text{HB-Bump}}$ increases with age by ~ 0.03 mag/Gyr. In case of $\Delta M_{F606W}^{\text{TO-Bump}}$, both TO and RGB-bump become fainter with increasing age, but the effect of changing t is larger on the TO luminosity. Overall $\Delta M_{F606W}^{\text{TO-Bump}}$ increases with age by ~ 0.08 mag/Gyr at $[\text{M}/\text{H}] = -2.0$, and by ~ 0.04 mag/Gyr at $[\text{M}/\text{H}] = -0.5$.

3. Comparison between theory and observations

The values of $\Delta M_{F606W}^{\text{TO-Bump}}$ measured in our sample of 12 clusters are displayed in the lower panel of Fig. 2, over-imposed to the theoretical calibration as a function of $[\text{M}/\text{H}]$ and age. The

² The BaSTI stellar evolution library is available at the following URL: <http://www.oa-teramo.inaf.it/BASTI>.

³ Our analysis relies entirely on the theoretical predictions from the BaSTI models. Although a good agreement does exist among several different stellar model libraries concerning the trend with age of the evolutionary features discussed in this paper, some small, marginal differences can still be present.

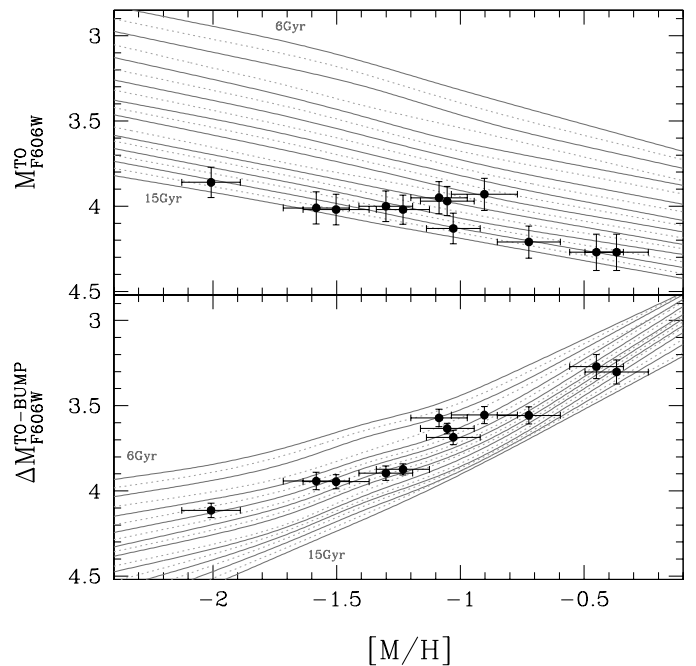


Fig. 2. *Upper panel:* Absolute M_{F606W} magnitude of the TO as a function of $[\text{M}/\text{H}]$ for our GC sample (filled circles). Solid and dashed lines display the theoretical calibration from BaSTI α -enhanced isochrones for ages between 6 and 15 Gyr, in steps of 0.5 Gyr. *Bottom panel:* As the upper panel but for $\Delta M_{F606W}^{\text{TO-Bump}}$.

cluster ages necessary to match the observed $\Delta M_{F606W}^{\text{TO-Bump}}$ appear generally younger than standard GC ages (of the order of 12–14 Gyr). The $\Delta M_{F606W}^{\text{TO-Bump}}$ ages and associated errors are reported in Table 1, as obtained by interpolation amongst the theoretical values. A conservative estimate of the associated error has been obtained by considering the rectangle defined in the $\Delta M_{F606W}^{\text{TO-Bump}} - [\text{M}/\text{H}]$ plane by the uncertainties in both $\Delta M_{F606W}^{\text{TO-Bump}}$ and $[\text{M}/\text{H}]$. The error in the age estimate has been then determined from the ages of the “youngest” and “oldest” corners of the rectangle. The same approach has been followed also to estimate the uncertainties in the ages from the absolute TO magnitude.

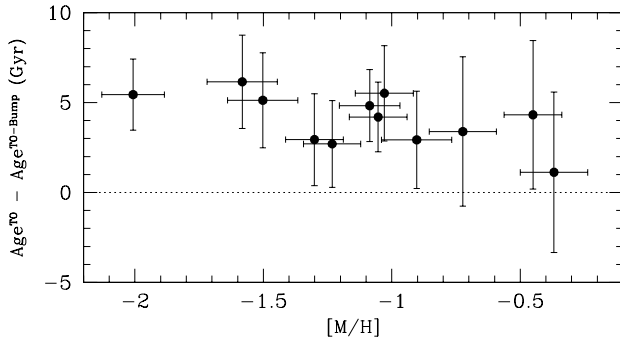
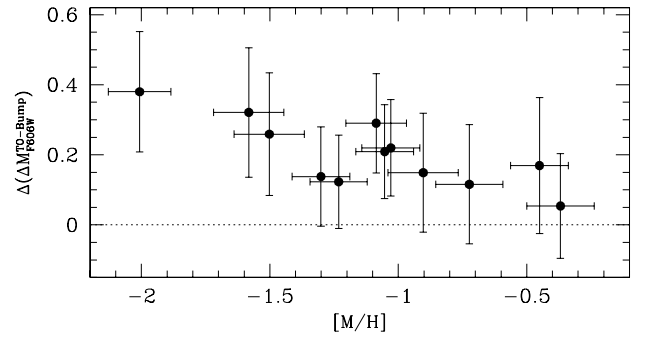
The upper panel of Fig. 2 displays a comparison between the theoretical calibration of the TO absolute magnitude (as a function of age and $[\text{M}/\text{H}]$) and the cluster TO absolute magnitudes M_{F606W}^{TO} (also reported in Table 1). A visual comparison of the upper and lower panels of Fig. 2 confirms that ages from $\Delta M_{F606W}^{\text{TO-Bump}}$ tend to be systematically lower than TO ages.

Figure 3 displays the difference between TO and $\Delta M_{F606W}^{\text{TO-Bump}}$ ages as a function of $[\text{M}/\text{H}]$. All points are systematically shifted to positive values of the age difference, and for about half of the clusters in the sample the difference is significant at the 2σ level or more. Another way to look at this discrepancy is to display the difference between the values of $\Delta M_{F606W}^{\text{TO-Bump}}$ expected from the cluster TO ages, and the measured values, as shown in Fig. 4. Conservative error bars on these $\Delta(\Delta M_{F606W}^{\text{TO-Bump}})$ values have been obtained applying a procedure analogous to the one followed to determine the errors on $\Delta M_{F606W}^{\text{TO-Bump}}$ ages. Figure 4 shows very clearly that the expected $\Delta M_{F606W}^{\text{TO-Bump}}$ values are systematically larger (as can

Table 1. The metal content, TO, RGB bump brightness, and age estimates from both TO and $\Delta M_{F606W}^{\text{TO-Bump}}$ for the selected sample of GCs.

Cluster	[Fe/H]	[α /Fe]	[M/H] ^a	$m_{F606W}(\text{TO})$	$M_{F606W}(\text{TO})$	$m_{F606W}(\text{Bump})$	Age(MSTO) ^b	Age($\Delta M_{F606W}^{\text{TO-Bump}}$) ^c
NGC0104	-0.76	0.42	-0.45±0.11	17.53±0.07	4.27±0.11	14.26±0.004	13.98±2.11	9.66±3.55
NGC0362	-1.30	0.30	-1.09±0.12	18.74±0.05	3.95±0.09	15.17±0.007	11.85±1.62	7.02±1.18
NGC1851	-1.18	0.38	-0.90±0.14	19.40±0.05	3.93±0.09	15.84±0.008	10.88±1.70	7.95±2.17
NGC5904	-1.33	0.38	-1.05±0.11	18.37±0.03	3.97±0.09	14.73±0.008	11.95±1.53	7.75±1.19
NGC6093	-1.75	0.24	-1.58±0.14	19.67±0.05	4.01±0.09	15.72±0.010	14.69±1.93	8.53±1.74
NGC6218	-1.33	0.41	-1.03±0.11	18.18±0.04	4.13±0.09	14.49±0.013	14.12±1.99	8.60±1.86
NGC6254	-1.57	0.37	-1.30±0.11	18.36±0.04	4.00±0.09	14.47±0.012	13.32±1.80	10.38±1.91
NGC6341	-2.35	0.46	-2.01±0.12	18.60±0.04	3.86±0.09	14.49±0.011	14.23±1.77	8.79±1.07
NGC6541	-1.82	0.43	-1.50±0.14	18.70±0.04	4.02±0.09	14.76±0.010	14.51±1.97	9.38±1.87
NGC6637	-0.59	0.31	-0.37±0.13	19.40±0.07	4.27±0.11	16.10±0.008	13.69±2.26	12.57±3.91
NGC6723	-1.10	0.50	-0.72±0.13	18.90±0.05	4.21±0.09	15.34±0.010	14.12±2.15	10.73±3.61
NGC6752	-1.55	0.43	-1.23±0.11	17.26±0.03	4.02±0.09	13.39±0.012	13.28±1.75	10.58±1.76

Notes. ^(a) The cluster global metallicity obtained by combining the [Fe/H] estimates from Carretta et al. (2009) and the average α -elements enhancement from Carretta et al. (2010a) according to Eq. 3 in Salaris et al. (1993). The associated error bar is obtained by propagating the errors in [Fe/H] and [α /Fe] discussed in Sect. 2. accordingly. ^(b) The cluster age in Gyr estimated by using the TO magnitude and the theoretical calibration shown in the upper panel of Fig. 2. ^(c) The cluster age in Gyr estimated by using the $\Delta M_{F606W}^{\text{TO-Bump}}$ parameter and the theoretical calibration shown in the lower panel of Fig. 2.


Fig. 3. Difference between the cluster ages inferred from the TO absolute magnitude and from $\Delta M_{F606W}^{\text{TO-Bump}}$.

Fig. 4. Difference between the values of $\Delta M_{F606W}^{\text{TO-Bump}}$ expected from the cluster TO ages, and the measured values, as a function of [M/H].

be also inferred from Fig. 2) than observed. The mean value of $\Delta(\Delta M_{F606W}^{\text{TO-Bump}})$ is equal to 0.20 mag, with a 1σ dispersion of ± 0.1 mag. A linear fit that takes into account the errors on both $\Delta(\Delta M_{F606W}^{\text{TO-Bump}})$ and [M/H] (using the routine fitexy in Press et al. 1992) provides a slope $d\Delta(\Delta M_{F606W}^{\text{TO-Bump}})/d[M/H] = -0.16 \pm 0.12$, that is not significantly different from zero. Neglecting the more discrepant cluster with [M/H] ~ -2.0 (NGC6341) leaves the mean value of $\Delta(\Delta M_{F606W}^{\text{TO-Bump}})$ almost unchanged (0.19 mag, with a 1σ dispersion of ± 0.08 mag), whilst the slope of the linear fit is again not statistically significant ($d\Delta(\Delta M_{F606W}^{\text{TO-Bump}})/d[M/H] = -0.14 \pm 0.14$).

4. Discussion

The main result of our analysis is summarized by Fig. 4, discussed in the previous section. The values of $\Delta M_{F606W}^{\text{TO-Bump}}$ predicted by theoretical models for cluster ages estimated from the TO absolute magnitudes, are larger than observed. Given that the observed TO magnitude is by definition matched by the theoretical isochrones to determine the TO age, this discrepancy implies that the absolute magnitude of the RGB-bump in the models is too bright.

An extension of this type of analysis to a larger, homogeneous sample of GC photometries is obviously desirable; how-

ever our results based on a limited sample of clusters provide already clear evidence of a real ‘over-luminosity’ of the predicted absolute magnitude of the RGB-bump, irrespective of problems with HB modelling and placement of the reference HB level in clusters with only blue HB stars.

The simplest explanation for this discrepancy envisages a systematic underestimate of the cluster metallicities by ~ 0.2 dex. An higher [M/H] would eliminate the discrepancy, because it causes a lower TO age and a lower theoretical RGB-bump brightness for each cluster. There is of course no indication that the metallicity scale we adopted is affected by this type of systematics, but this is a point to be considered.

In the following we expand our discussion to see how improvements in the micro- (e.g. opacities, nuclear reaction rates) and macro-physics (e.g., element transport mechanisms) employed in stellar evolution calculations, and the recently established presence of multiple stellar populations with varying chemical patterns in individual GCs, can account for this discrepancy.

4.1. Improved micro- and macro-physics

A straightforward explanation for the discrepancy highlighted in Fig. 4 could be an underestimate of the radiative opacity at temperatures around a few 10^6 K – typical temperatures at the lower

boundary of the convective envelope. Higher opacities would shift the convection boundary – hence the H-abundance discontinuity – to deeper layers, causing a fainter RGB-bump. However, this solution does not seem plausible, for the following reasons: i) radiative opacities in this temperature range should not be affected by an uncertainty larger than $\sim 5\%$ (see, e.g. Guzik 2008) and this small change is not able to reconcile theory with observations; ii) the discrepancy theory-observations increases with decreasing $[M/H]$, and it does not seem very likely that radiative opacities become less accurate when the metal content decreases.

The isochrones employed to determine both the cluster ages from the TO brightness, and the theoretical values of $\Delta M_{F606W}^{TO-Bump}$, do not account for the effect of atomic diffusion (including radiative levitation). Although current spectroscopic observations of globular cluster stars show that atomic diffusion is at least partially inhibited by additional turbulence/mixing (see, i.e. Korn et al. 2007) – induced for example by rotation (see, i.e., Eggenberger et al. 2010) – we summarize here the effect on TO ages and $\Delta M_{F606W}^{TO-Bump}$ values in case of full efficiency. According to the results by Vandenberg et al. (2002) and Michaud et al. (2010) – that expand upon previous studies by Cassisi et al. (1997, 1998) where the effect of radiative levitation was not considered – atomic diffusion makes the RGB-bump magnitude brighter by 0.03-0.06 mag at fixed age, and also decreases the cluster TO ages by at most ~ 1.5 Gyr for the lowest metallicity clusters. The combined effect on $\Delta M_{F606W}^{TO-Bump}$ would decrease the discrepancy for the most metal poor cluster in our sample by ~ 0.05 mag at most. The effect becomes less significant with increasing metallicity.

On the other hand, the recent redetermination of the $^{14}N(p, \gamma)^{15}O$ reaction rate – not included in our adopted models – would increase the cluster ages by ~ 1 Gyr, and at the same time make the RGB-bump brighter by ~ 0.06 mag at fixed age (Weiss et al. 2005; Pietrinferni et al. 2010). The net result would be an increase of the discrepancy by ~ 0.10 mag or more, **that would move the mean value of $\Delta(\Delta M_{F606W}^{TO-Bump})$ up to ~ 0.30 mag.** Overall, the combined effect of the new $^{14}N(p, \gamma)^{15}O$ reaction rate and inclusion of atomic diffusion (plus radiative levitation) **would exacerbate the discrepancy between theory and observations, that would become on average of the order of 0.25 mag.**

Another possibility to mitigate the discrepancy is to include overshooting beyond the formal boundary of the convective envelope (see, e.g., Alongi et al. 1991). Calculations by Cassisi et al. (2002) show that the inclusion of convective overshooting decreases the RGB-bump brightness by $\sim 0.8\text{mag}/H_p$ (where H_p denotes the local pressure scale height); the discrepancy between theory and observations would disappear with the inclusion of convective overshooting of the order of ~ 0.25 below the Schwarzschild boundary of the convective envelope.

Besides overshooting from the convective boundary, Cassisi et al. (2002) have investigated also the effect on the RGB-bump shape and brightness, of a smoother chemical discontinuity left over by the first dredge-up. A smoother chemical discontinuity could be produced, for example, by turbulent mixing counteracting the efficiency of atomic diffusion. Cassisi et al. (2002) results show that the bump luminosity decreases by $\sim 0.25\text{mag}/H_p$, where the smoothing length is expressed in units of the local pressure scale height. Given that smoothing the discontinuity alters also the shape of the RGB luminosity function in the bump region, this hypothesis is potentially testable. As estimated by Cassisi et al. (2002), a sample of more than 120 RGB stars within

± 0.2 mag of the peak of the RGB-bump, and random photometric errors smaller than 0.03 mag can potentially disclose this effect in the RGB luminosity function.

4.2. The role of GC multipopulations

A very important issue to be considered, is the effect on the cluster RGB-bump luminosity and TO ages of subpopulations with varying degrees of the CNO anticorrelation and the – likely – associated increased He abundance, as observed in individual GCs (see, e.g., Gratton et al. 2004, for a review). If the sum of the CNO abundance stays constant among all stars in a given cluster – as observed, within the measurement errors – the RGB-bump magnitude is affected only by the possible increase of helium. As shown by, e.g., Cassisi & Salaris (1997) and Salaris et al. (2006), increasing the initial He abundance increases the bump brightness at fixed age and $[Fe/H]$. In a 'real' cluster the size of this effect depends on the exact amount of He-enhancement and the fraction of stars involved, but the main point is that this can only exacerbate the discrepancy displayed in Fig. 4. As for the ages from the TO luminosity, one has to notice that within the individual clusters analyzed in this paper, there are no clear signs of large spreads of the initial He abundance, in terms of a split of the MS in the CMD. A reasonable upper limit to the He spread of 0.05 in mass fraction, would decrease the TO age by not more than ~ 0.5 Gyr (see, i.e., Salaris et al. 2006). As a conclusion, the effect of subpopulations with enhanced He within individual clusters in our sample would not solve the discrepancy highlighted by Fig. 4.

Only NGC 1851 shows a clear split of the subgiant branch in our adopted CMD, whose origin is still debated (see, e.g., Cassisi et al. 2008; Carretta et al. 2010b). The TO measurement has been obtained considering only the most populated SGB, that should harbour stars with a 'standard' He and metal distribution (Cassisi et al. 2008) so that also in this case our TO age estimates should be reliable.

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References

- Alongi, M., Bertelli, G., Bressan, A., & Chiosi, C. 1991, *A&A*, 244, 95
- Alves, D. R., & Sarajedini, A. 1999, *ApJ*, 511, 225
- Anderson, J. et al. 2008, *AJ*, 135, 2055
- Bedin, L.R., Cassisi, S., Castelli, F., Piotto, G., Anderson, J., Salaris, M., Momany, Y., & Pietrinferni, A. 2005, *MNRAS*, 357, 1038
- Bjork, S. R., & Chaboyer, B. 2006, *ApJ*, 641, 1102
- Bono, G., Cassisi, S., Zoccali, M., & Piotto, G. 2001, *ApJ*, 546, L109
- Carretta, E., Bragaglia, A., Gratton, R., D'Orazi, V., & Lucatello, S. 2009, *A&A*, 508, 695
- Carretta, E., Bragaglia, A., Gratton, R. G., Recio-Blanco, A., Lucatello, S., D'Orazi, V. & Cassisi, S. 2010, *A&A*, 516, A55
- Carretta, E. et al. 2010, *ApJ*, 772, L1
- Caputo, F., & Cassisi, S. 2002, *MNRAS*, 333, 825
- Cassisi, S., & Salaris, M. 1997, *MNRAS*, 285, 593
- Cassisi, S., Degl'Innocenti, S., & Salaris, M. 1997, *MNRAS*, 290, 515
- Cassisi, S., Castellani, V., degl'Innocenti, S., & Weiss, A. 1998, *A&AS*, 129, 267
- Cassisi, S., Castellani, V., Degl'Innocenti, S., Salaris, M., & Weiss, A. 1999, *A&AS*, 134, 103
- Cassisi, S., Salaris, M., & Bono, G. 2002, *ApJ*, 565, 1231
- Cassisi, S., Salaris, M., Pietrinferni, A., Piotto, G., Milone, A. P., Bedin, L. R., & Anderson, J. 2008, *ApJ*, 672, L115

- Cassisi, S. 2010, in proceedings of IAU Symposium 262, G. Bruzual & S. Charlot eds., p.13
- Di Cecco, A., et al. 2010, ApJ, 712, 527
- Eggenberger, P., Meynet, G., Maeder, A., Miglio, A., Montalbán, J., Carrier, F., Mathis, S., Charbonnel, C., & Talon, S. 2010, A&A, 519, A116
- Fusi Pecci, F., Ferraro, F. R., Crocker, D. A., Rood, R. T., & Buonanno, R. 1990, A&A, 238, 95
- Gratton, R. G., Bragaglia, A., Carretta, A., Clementini, G., Desidera, S., Grundahl, F., & Lucatello, S. 2003, A&A, 408, 529
- Iben, I., Jr. 1968, ApJ, 154, 581
- King, C. R., Da Costa, G. S., & Demarque, P. 1985, ApJ, 299, 674
- Kippenhahn, R., & Weigert, A. 1994, 'Stellar Structure and Evolution', (Germany: Springer-Verlag)
- Korn, A.J., Grundahl, F., Richard, O., Mashonkina, L., Barklem, P.S., Collet, R., Gustafsson, B., & Piskunov, N. 2007, ApJ, 671, 402
- Gratton, R. G., Sneden, C., & Carretta, E. 2004, ARA&A, 42, 385
- Guzik, J.A. 2008, Mem. Soc. Astron. It., 79, 481
- Marín-Franch, A., Aparicio, A., Piotto, G., Rosenberg, A., Chaboyer, B., Sarajedini, A., Siegel, M., et al. 2009, ApJ, 694, 1498
- Meissner, F., & Weiss, A. 2006, A&A, 456, 1085
- Michaud, G., Richer, J., & Richard, O. 2010, A&A, 510, 104
- Monelli, M. et al., 2010, ApJ, 718, 707
- Pietrinferni, A. et al. 2004, ApJ, 612, 168
- Pietrinferni, A., Cassisi, S., Salaris, M., & Castelli, F. 2006, ApJ, 642, 797
- Pietrinferni, A., Cassisi, S., & Salaris, M. 2010, A&A, 522, 76
- Piotto, G. 2008, Mem. Soc. Astron. It., 79, 334
- Press, W. H., Teukolsky, S. A., Vetterling, W. T. & Flannery, B. P. 1992, in "Numerical recipes in FORTRAN. The art of scientific computing", Cambridge: University Press, 2nd ed.
- Renzini, A. & Fusi Pecci, F. 1988, ARA&A, 26, 199
- Riello, M., et al. 2003, A&A, 410, 553
- Salaris, M., Chieffi, A., & Straniero, O. 1993, ApJ, 414, 580
- Salaris, M., Cassisi, S., & Weiss, A. 2002, PASP, 114, 375
- Salaris, M., & Cassisi, S. 2005, 'Evolution of Stars and Stellar Populations', London, Wiley and sons eds.
- Salaris, M., Weiss, A., Ferguson, J.W., & Fusilier, D. J. 2006, ApJ, 645, 1131
- Sarajedini, A. et al. 2007, AJ, 133, 1658
- Sirianni, M. et al. 2005, PASP, 117, 1049
- Stetson, P. B. 1994, PASP, 106, 250
- Thomas, H. C. 1967, Ph.D. thesis, L.M. Univ., München
- VandenBerg, D.A., Richard, O., Michaud, G., & Richer, J. 2002, ApJ, 571, 487
- Weiss, A., Serenelli, A., Kitsikis, A., Schlattl, H., & Christensen-Dalsgaard, J. 2005, A&A, 441, 1129
- Zinn, R., & West, M. J. 1984, ApJS, 55, 45
- Zoccali, M., Cassisi, S., Piotto, G., Bono, G., & Salaris, M. 1999, ApJ, 518, L49