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ON THE OBSERVATIONAL PROPERTIES OF He-BURNING STARS: SOME CLUES ON THE TILT OF THE HORIZONTAL BRANCH IN METAL-RICH CLUSTERS

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ABSTRACT

We investigate the predicted color-magnitude distribution of metal-rich horizontal-branch (HB) stars, discussing selected theoretical models computed under various assumptions about the star metallicity and the efficiency of superadiabatic convection. We find that canonical zero-age horizontal branches with metallicity larger or of the order of $Z = 0.002$ should all be affected by a tilt by an amount that increases when the metallicity is increased and/or the mixing length is decreased, reaching a tilt of $\Delta V \sim 0.2$ mag in the case of solar metallicity when a mixing-length value $\alpha = 1.6$ is assumed (ΔV is the magnitude difference between the top of the blue HB and the fainter magnitude reached by the red HB). Uncertainties in the luminosity of the red HB due to uncertainty in the mixing-length value are discussed. We finally discuss the much larger tilt observed in the clusters NGC 6441 and NGC 6388, reporting additional evidence against suggested noncanonical evolutionary scenarios. Numerical experiments show that differential reddening could produce such sloped HBs. Furthermore, *Hubble Space Telescope* planetary-camera imaging of NGC 6441 gives clear indications of the occurrence of differential reddening across the cluster. However, the same imaging shows that the observed slope of the red HB *is not* an artifact of differential reddening. We finally show that sloping red HBs in metal-rich clusters are a common occurrence not necessarily correlated with the appearance of extended blue HBs.

Subject headings: globular clusters: general — globular clusters: individual (NGC 6388, NGC 6441) — stars: evolution — stars: horizontal-branch

1. INTRODUCTION

In a recent paper, Brocato et al. (1999, hereafter Paper I), we present the case of the intermediate-metallicity globular cluster NGC 6362, where horizontal-branch (HB) stars reach a maximum V luminosity at $B-V \sim 0.2$ mag, with an overall tilt of the order of $\Delta V \sim 0.1$ mag: thus, of the same order of magnitude as the tilted HB already observed in NGC 1851 (Walker 1998), possibly in NGC 6229 (Borissova et al. 1999), and in NGC 6712 (Ortolani et al. 2000). In the same paper, it was shown that canonical predictions concerning low-mass, He-burning stars with $Z = 0.002$ do foresee such an occurrence, nicely accounting for the observed NGC 6362 HB stars distribution. Thus, we regard such a tilt as an evolutionary feature that should characterize all the well-populated intermediate-metallicity clusters when observed with sufficient photometric accuracy.

The evidence for such a "canonical" tilt being due to the behavior of the bolometric correction appears to be of some relevance in connection with the debated problem of the much larger tilts ($\Delta V \sim 0.5$ mag) observed in some metal-rich globulars of the inner Milky Way. The first evidence for similar unexpectedly large tilts was brought to light from *Hubble Space Telescope* (*HST*) observations of the globulars NGC 6388 and NGC 6441 (Piotto et al. 1997; Rich et al. 1997). Sweigart & Catelan (1998) drove attention toward such a feature, regarding it as observational evidence requiring noncanonical evolutionary scenarios. In this paper we investigate evolutionary predictions concerning the color-magnitude (CM) distribution of metal-rich HB stars. In the next section we present new sets of canonical HB models, whereas § 3 deals with their CM diagrams and theoretical uncertainties due to the efficiency of the convection in superadiabatic layers, which affects the predicted luminosity of stars at the red HB end. In § 4 we provide arguments and constraints to understand the origin of the large tilt of the high-metallicity clusters NGC 6441 and NGC 6388. Final remarks close the paper.

2. METAL-RICH ZERO-AGE HORIZONTAL-BRANCH MODELS

The recent literature has already devoted considerable attention to metal-rich HB structures. Starting from the pioneering paper by Horch, Demarque, & Pinsonneault (1992), several works have been presented covering this issue with rather detailed evaluations (Dorman, Rood, & O'Connel 1993; Fagotto et al. 1994; Yi, Demarque, & Kim 1997; Bono et al. 1997; Girardi et al. 2000). However, these studies have been mainly devoted to investigating the evolution of HB structures in connection with either the UV excess in elliptical galaxies or the pulsational properties of metal-rich RR Lyrae variables, and to our knowledge, up to recent times no attention was devoted to the predicted distribution of metal-rich HB stars in the CM diagram. To investigate such an issue, we decided to extend the evolutionary computa-

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TABLE 1

SELECTED EVOLUTIONARY QUANTITIES AT THE HE IGNITION FOR DIFFERENT ASSUMPTIONS ABOUT THE RGB PROGENITOR AND THE CHEMICAL COMPOSITION

Y_{MS}	Z	M_{RGB} ($M_\odot$)	$M_{c,He}$ ($M_\odot$)	Y_{sup}	Age^{tip} (Gyr)	$\log(L/L_\odot^{tip})$
0.23...	0.002	0.9	0.501	0.23	10.23	3.42
0.25...	0.006	0.9	0.492	0.26	11.75	3.44
0.28...	0.02	1.0	0.481	0.29	11.22	3.47

tions given in Paper I for $Z = 0.002$ to higher metallicities. Similar computations have been recently presented by VandenBerg et al. (2000) but for a more restricted range of metallicity, not addressing the problem of tilt. However, this allows a useful comparison between the results of the two theoretical scenarios for a common value of Z.

In this paper, zero-age horizontal-branch (ZAHB) models have been produced by following selected stellar models all along their H-burning phase until the ignition of the He flash, deriving in this way the mass of the He core of newborn He-burning stars with an age of the order of 10 Gyr, in agreement with several recent estimates of the age of metal-rich globular clusters (Salaris & Weiss 1997; Gratton et al. 1997; Chaboyer et al. 1998; Cassisi et al. 1999). For a detailed discussion on the physical inputs adopted in the computations, we refer to Cassisi et al. (1998). Table 1 gives selected parameters for the above quoted models. Left to right, one finds original He abundance, metallicity and mass of the model, mass of the He core at the He ignition, surface He abundance after the first dredge up, and finally, star age and luminosity at the red giant branch (RGB) tip.

As shown in Table 1, to extend the investigation in Paper I to higher metallicities, we selected two "suitable" values of Z, choosing $Z = 0.006$ as representative of "metal-rich" clusters such as 47 Tuc, and $Z = 0.02$ as a safe upper limit for globular-cluster metallicities. As in Paper I, the present computations have been performed by adopting a mixing-length parameter $\alpha = 1.6$, implemented with the case $\alpha = 1.0$ to explore the effect of mixing-length assumptions. Figure 1 gives the predicted distribution of these models in the $\log(L/L_\odot)$–$\log T_e$ HR diagram. As labeled in the figure, the amount of original He (Y_{MS}) has been increased with Z according to $\delta Y/\delta Z \sim 2.5$, as suggested by current evaluation on that matter (see, e.g., Peimbert 1995; Fernandes et al. 1998). As a whole, one finds that data in both Table 1 and Figure 1 appear in general agreement with previous evaluations given by Dorman et al. (1993) and Yi et al. (1997), our models being slightly brighter as a consequence of larger initial He cores (as discussed in Cassisi et al. 1998).

As expected, Figure 1 shows that the effective temperature of red HB stars depends on the assumption about the mixing length. This implies that at any given temperature, the luminosity of the red portion of the ZAHB depends on the assumptions about the mixing length, increasing when the mixing length increases. This dependence grows with the stellar metallicity, since at higher metallicities the HB locus moves toward lower effective temperatures and red HB stars are increasingly affected by external convection, making stellar models more sensitive to the adopted efficiency of the superadiabatic convection. As we discuss in the next section, this will leave some uncertainty in theoretical predictions on tilted HB.

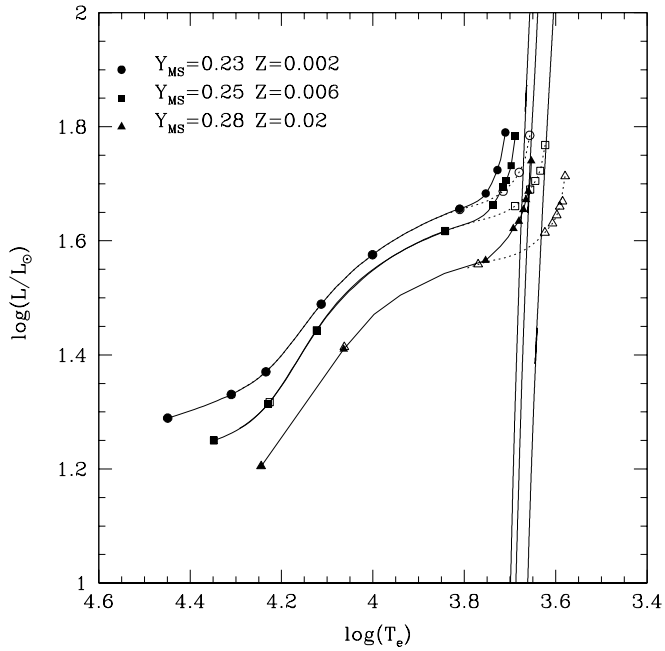

FIG. 1.—ZAHB loci in the theoretical $\log(L/L_\odot)$–$\log T_e$ plane for the labeled chemical compositions (Y_{MS}, Z) and for two different assumptions about the mixing-length parameter ($\alpha = 1.0$, *dotted lines and open symbols*; $\alpha = 1.6$, *solid lines and filled symbols*). Symbols along the ZAHB give the location of models with masses 0.505 (0.508 for $Z = 0.002$), 0.53, 0.55, 0.58, 0.60, 0.63, 0.65, 0.70, and 0.90 $M_\odot$, respectively. The location of the corresponding RGBs in the case $\alpha = 1.6$ is also shown, with metallicity increasing left to right.

3. THE COLOR-MAGNITUDE DIAGRAM MORPHOLOGY OF METAL-RICH HBs

Making use of model atmospheres by Castelli, Gratton, & Kurucz (1997), previous results have been translated into CM diagrams. Figure 2 shows the predicted location of the computed ZAHB sequences in the (M_V, $B-V$) and (M_V, $V-I$) diagrams for the two choices of the mixing length. The same figure shows the predicted location of the corresponding RGBs for $\alpha = 1.6$, which gives a reasonable approximation to the observed RGB colors when adopting the above atmosphere models (Cassisi et al. 1998). In the investigated range of metallicity, all the ZAHBs, for each adopted value of the mixing length, show a canonical tilt by an amount that is largest at the highest explored metallicity. As a matter of fact, the dependence on the metallicity already discussed in the previous section is now amplified by the parallel increase of the bolometric correction as the stellar temperatures decrease.

By relying on the reasonable accuracy of an adopted model of atmospheres, RGB models with a mixing-length parameter as low as $\alpha = 1.0$ are ruled out, since they would have exceedingly red colors (see, for example, Fig. 3 in Paper I). Thus, if one takes $\alpha = 1.6$ for the actual RGB stars and assumes a common value of the mixing length in both RGB and HB structures, canonical theory predicts a tilt growing from $\Delta V \sim 0.05$ mag when $Z = 0.002$ up to $\Delta V \sim 0.2$ mag when $Z = 0.02$.

On the other hand, if one assumes a less efficient convection in red HB stars (i.e., a shorter mixing length) than in RGB structures, this tilt could increase, as shown in Figure 2. In such a case, one could invoke either an exceedingly larger cluster age or a nonnegligible amount of mass loss to

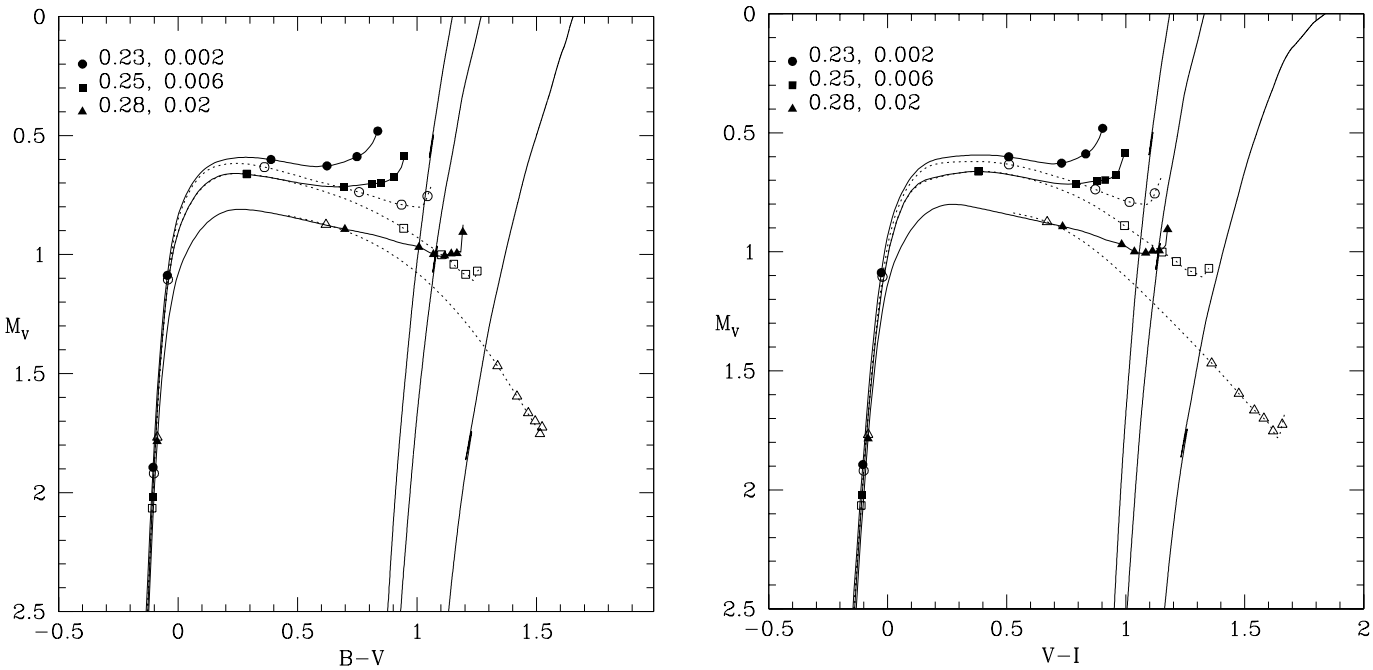

FIG. 2.—ZAHBs and RGBs as in Fig. 1, but in the observational (M_V, $B-V$)- and (M_V, $V-I$)-planes

avoid the HB crossing the RGB, an occurrence that would run against well-established observational evidence. However, such a scenario appears rather artificial, so we base the following discussion on the predictions for the case of $\alpha = 1.6$ as a reasonable approximation of actual stellar structures, suggesting that the above uncertainty on the tilt should hardly exceed few hundredths of magnitude.

Such a canonical tilt can obviously be observed only in clusters with a ZAHB covering a suitable range of temperatures, whereas for those with only red HBs, one would detect only the sloping red portion of the branch. According to the HB models presented here, over the range $0.5 < B-V < 1.0$, the predicted slope for the solar metallicity is of the order of $dM_V/d(B-V) \sim 0.24$. For even redder colors, models reach their redder HB limit, and luminosity starts increasing with the mass as earlier predicted by Caloi, Castellani, & Tornambé (1978).

One has also to discuss whether evolutionary effects can mask the discussed ZAHB distribution. Figure 3 shows the evolutionary paths of selected HB models for the two given choices of metallicity. For $Z = 0.006$, all the evolutionary tracks lie above the ZAHB locus, so that the lower envelope of the observed distribution keeps being defined by the ZAHB, thus preserving the sloping behavior discussed in this section. This is not the case for solar metallicities, for which the ZAHB is crossed by the model having the blue hook just below the point at which its luminosity is at maximum. However, such an occurrence will decrease the tilt by less than 0.009 mag, thus again substantially preserving the predicted canonical tilt.

Let us finally compare our results with evolutionary data recently presented by VandenBerg et al. (2000). Inspection of Figure 3 in that paper (*bottom panel*) discloses that in the case of $[\alpha/\mathrm{Fe}] = 0$, increasing the metallicity causes a tilt to appear, reaching a maximum value of the order of $\Delta V \sim 0.08$ mag at the largest investigated metallicity, $Z = 0.01$. From data shown in our Figure 2, one finds $\Delta V \sim 0.06$ mag when $Z = 0.006$ and $\Delta V \sim 0.18$ mag for solar metallicity. By a linear interpolation on $\log Z$, it follows that $\Delta V \sim 0.10$ at $Z = 0.01$, i.e., one finds that both results appear in reasonable agreement, with VandenBerg et al. predicting marginally smaller tilts.

One can further discuss the origin of the marginal difference, bearing in mind that the predicted tilt is the combined result of both ZAHB models and bolometric corrections. Luckily enough, the comparison of Figure 1 of both papers discloses that we have a quite similar treatment of external convection, since ZAHB models with the same chemical composition reach a quite similar minimum temperature. Thus, the difference is not an effect of the already discussed dependence of the tilt on the mixing length. On the contrary, there are several differences both in modeling stellar structures and in color transformations that could be at the origin of the differences. We do not use the same approach for the conductive opacities (Itoh et al. 1983) in our computations against Hubbard & Lampe (1969) or for the equation of state (EOS) (Rogers, Swenson, & Iglesias 1996) against an improved version of the VandenBerg (1992) EOS, and in particular, our program takes into account element sedimentation all along the pre-HB evolutionary phases (Castellani et al. 1997). Moreover, we use the color–effective temperature transformations and the bolometric correction scale by Castelli et al. (1997) against Bell & Gustafsson (1989) and VandenBerg & Bell (1985). When all these differences are taken into account, one can conclude that the reasonable agreement between the present and the VandenBerg et al. (2000) results can be taken as encouraging evidence for the reality of tilted HBs as a well-established feature in all modern canonical HB models.

4. THE CASES OF NGC 6441 AND NGC 6388

In the previous section we have found that canonical HB models predict moderately tilted HB morphologies. However, in the well-known cases of NGC 6388 and NGC 6441, one finds evidence for a tilt of the order of $\Delta V \sim 0.5$ mag,

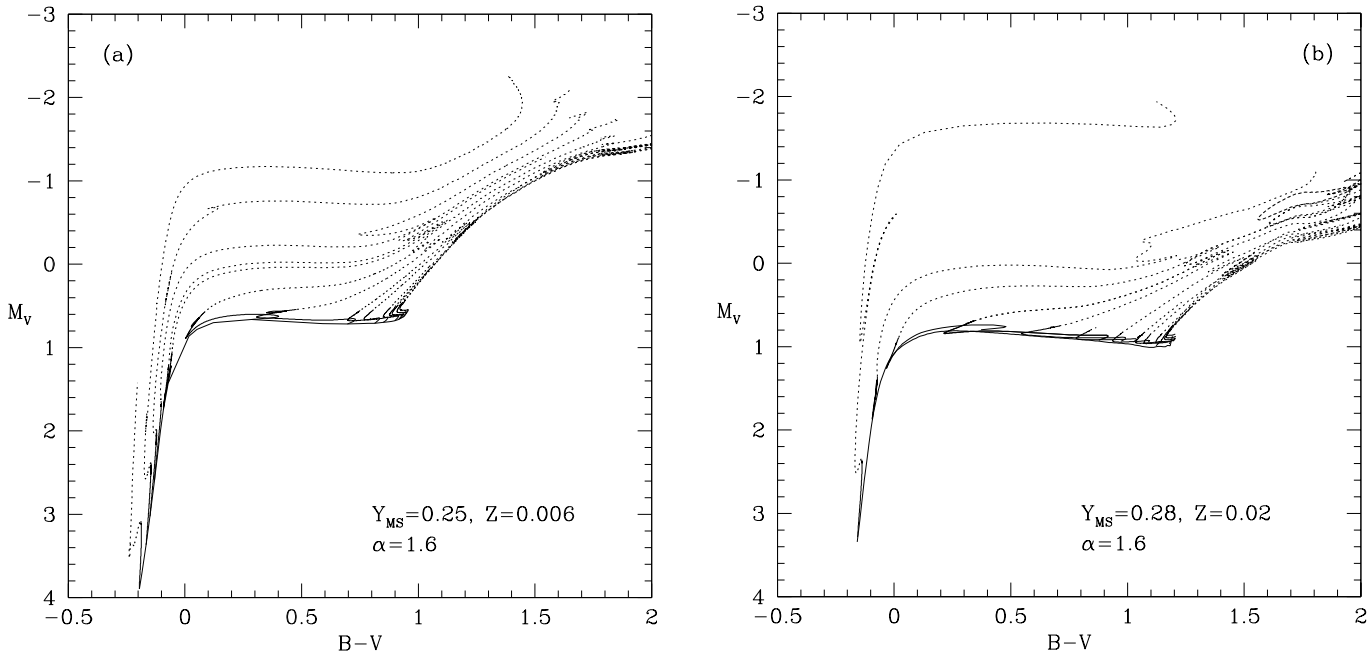

FIG. 3.—(*a*) Selected sample of evolutionary tracks with $Z = 0.006$, $Y_{MS} = 0.25$, and $\alpha = 1.6$, and the corresponding ZAHB in the observational (M_V, $B-V$)-plane. Dotted lines refer to the final phases of He-burning, when the central He abundance is lower then $Y_c = 0.1$. (*b*) As in (*a*), but for $Z = 0.02$ and $Y_{MS} = 0.28$.

i.e., definitely much larger than predicted on canonical theoretical grounds. In the light of such evidence, in this section let us discuss observational data for these clusters in order to gain further information on observational evidence on that matter. For the sake of discussion, Figure 4 gives the CM diagram of NGC 6441 as derived from *HST* observations (G. Piotto et al., in preparation), with clear evidence for the above-mentioned tilt.

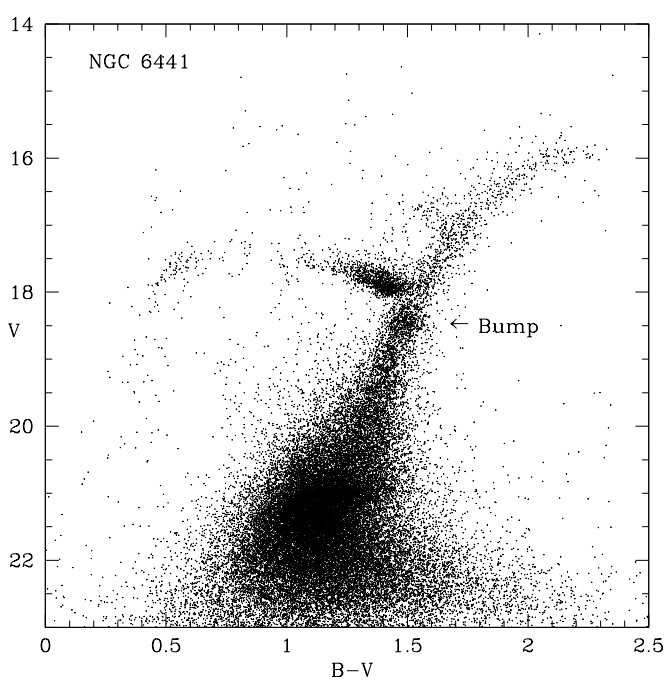

FIG. 4.—Plot of (V, $B-V$)-diagram of NGC 6441. The arrow shows the observed location of the RGB bump.

To be conservative, one cannot easily exclude a contribution to the observed tilt from stars evolved from the blue HB tail, crossing the CM diagram at $(B-V)_0 \sim 0$ at luminosities larger than the ZAHB location. However, as first noted by Piotto et al. (1997) and recently reinforced by Pritzl et al. (2001), the cluster appears peculiar not only for the tilted nature of the whole HB but also for the slope of the HB red portion. As shown in Figure 4, the lower envelope of observed HB stars runs as $dV/d(B-V) \sim 1.5$. Comparison with theoretical predictions, as given in the previous Figure 3, shows that in this respect, canonical theory also cannot account for such a feature.

4.1. *Noncanonical Scenarios*

In both NGC 6441 and NGC 6388, the evidence for the tilt is accompanied by the parallel and unexpected occurrence of an extended, extremely blue HB, against the general red morphology of metal-rich HBs. Thus, one is tempted to speculate whether the tilt and the " blue tail " both originate from a common mechanism. As a matter of fact, Sweigart & Catelan (1998) already suggested three noncanonical scenarios accounting for these features, as given by (1) abnormally high original Y abundances, (2) a spread in He cores due to stellar rotation, and (3) differential deep mixing along the RGB. However, the occurrence of an extremely high original Y in this cluster has been already discarded by Layden et al. (1999) on the basis of the R method, whereas Moehler, Sweigart, & Catelan (1999) found that spectroscopic results for blue HB stars in these clusters are inconsistent with all three of these noncanonical scenarios.

In this context, let us drive the attention toward additional observational evidence running against these three noncanonical suggestions, as given by the occurrence of a well-defined " bump " along the RGBs of both clusters. The occurrence of these bumps is clearly detectable in the origi-

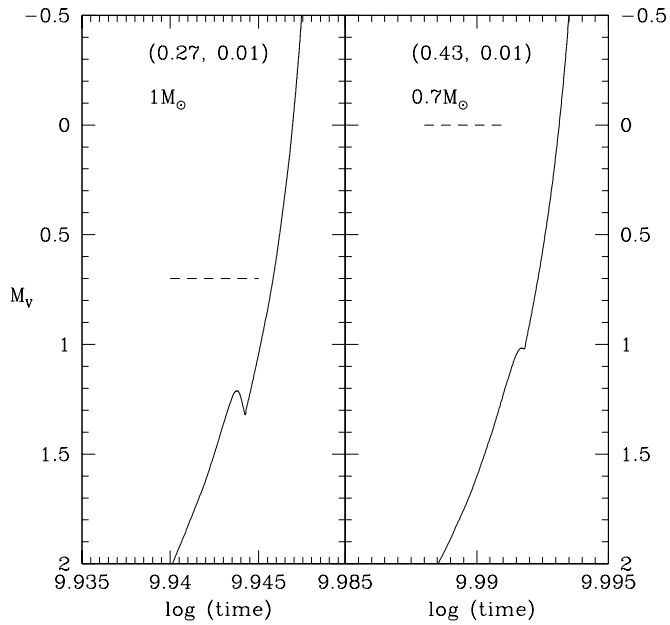

FIG. 5.—Theoretical RGBs for a cluster age of the order of 10 Gyr, $Z = 0.01$, and two different assumptions about the original helium content $Y_{MS} = 0.27$ ($M = 1.0\ M_\odot$) and $Y_{MS} = 0.43$ ($M = 0.7\ M_\odot$). The dashed lines show the corresponding predictions about the HB luminosity level.

nal paper by Rich et al. (1997) for both NGC 6388 and NGC 6441. Zoccali et al. (1999) have already discussed the RGB bump in NGC 6388, showing that the luminosity of the bump appears in reasonable agreement with theoretical predictions. Here we suggest that the bump could hardly survive a spread either in stellar rotation or in deep mixing, whereas the " high-helium " scenario runs against the observations. In fact, the data in Figure 4 disclose that, like NGC 6388, NGC 6441 also shows a well-defined RGB bump below the HB luminosity level at $V \sim 18.5$ mag. As shown in the left panel of Figure 5, such a feature appears in fine agreement with canonical expectations for $Y_{MS} = 0.27$. On the contrary, the assumption of an original He content as large as $Y_{MS} = 0.43$ would produce quite a small bump, and at too low a luminosity with respect to the HB luminosity level (Fig. 5, *right panel*), at odds with the observations. Thus, the conclusions of Layden et al. (1999) are supported on a firmer theoretical basis, i.e., by using the RGB bump, which is an observational feature not affected by the typical uncertainties of HB lifetimes involved in the *R*-parameter calibration (Cassisi et al. 1998).

4.2. *Spread in Metallicity*

In the recent literature, it has been repeatedly suggested that the peculiar HB in the two clusters could be connected with a spread in the metallicity of cluster stars (Piotto et al. 1997; Sweigart 2002; Pritzl et al. 2001). To discuss this point, we can take advantage of the well-developed blue HB of NGC 6388, covering the abrupt decrease of magnitude defined as the HB–turning down (HB-TD) in Brocato et al. (1998). According to the discussion given in that paper, one can safely assume the HB-TD as an indicator of intrinsic CM location, independently of HB metallicities. This allows a meaningful comparison of the CM diagram of NGC 6388 with a similar diagram for less metal rich clusters. To perform such a comparison, we choose from the Padova *HST* snapshot database the CM diagram for two clusters showing a well-developed HB blue tail, namely, NGC 7099 ([Fe/H] = −2.12) and NGC 2808 ([Fe/H] = −1.15), both metallicities in Zinn and West scale.

The results of such a procedure, as disclosed in Figure 6, allow us to put firm constraints on the presence of metal-poor stellar populations in NGC 6388. If the blue HB stars in this cluster originated from metal-poor progenitors, one should expect along the luminous portion of the RGB as many RGB stars as in the blue HB phases, since the predicted ratio *R* of HB to RGB stars above the HB luminosity

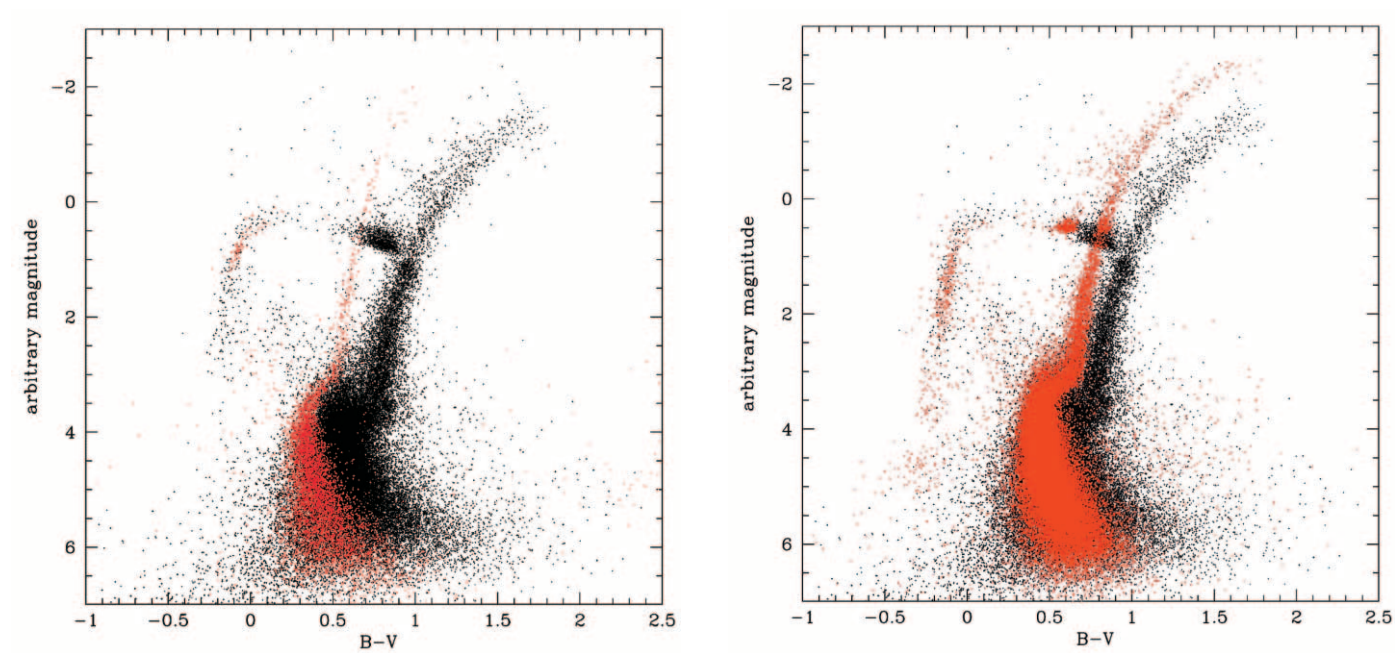

FIG. 6.—*Left*: CM diagram of NGC 7099, forced to match the blue side of the HB of NGC 6388. *Right*: Same, but for the more metal rich cluster NGC 2808.

level is of the order of unity (see, e.g., Zoccali et al. 2000). Since the blue HB of NGC 6388 contains 202 stars, one can be confident that the lack of observational evidence of RGB stars in the expected regions in the NGC 6388 diagram excludes the occurrence of metal-poor giants with the given metallicities. One concludes that in NGC 6388, blue HB stars must have originated from RG progenitors with metallicity larger than the metallicity of NGC 2808, namely, larger than $[\mathrm{Fe/H}] = -1$, leaving little room for the hypothesis of a spread in metallicity.

4.3. *The Role of Differential Reddening*

In order to save canonical predictions, it has already been suggested that differential reddening in these heavy reddened clusters could play a relevant role. The occurrence of differential reddening in NGC 6441 has already been suggested by Piotto et al. (1997). Layden et al. (1999) have recently discussed their ground-based CCD photometry of NGC 6441, confirming that cluster stars are affected by a rather strong differential reddening. By noticing that the slope of the HB runs according to the reddening vector, these authors conclude that differential reddening should partially contribute to the observed slope. To look into this problem, we took advantage of *HST* observation, looking for the features of CM diagrams in selected cluster areas. As reported in Figure 7, we extracted from the $36''.4 \times 36''.4$ image of the planetary camera 16 ($9''.1 \times 9''.1$) subimages, comparing the CM diagrams of the various areas with the RGB ridge line of area 6 taken as a reference. The size of each small area is chosen in order to have a reasonable number of stars in the corresponding RGB.

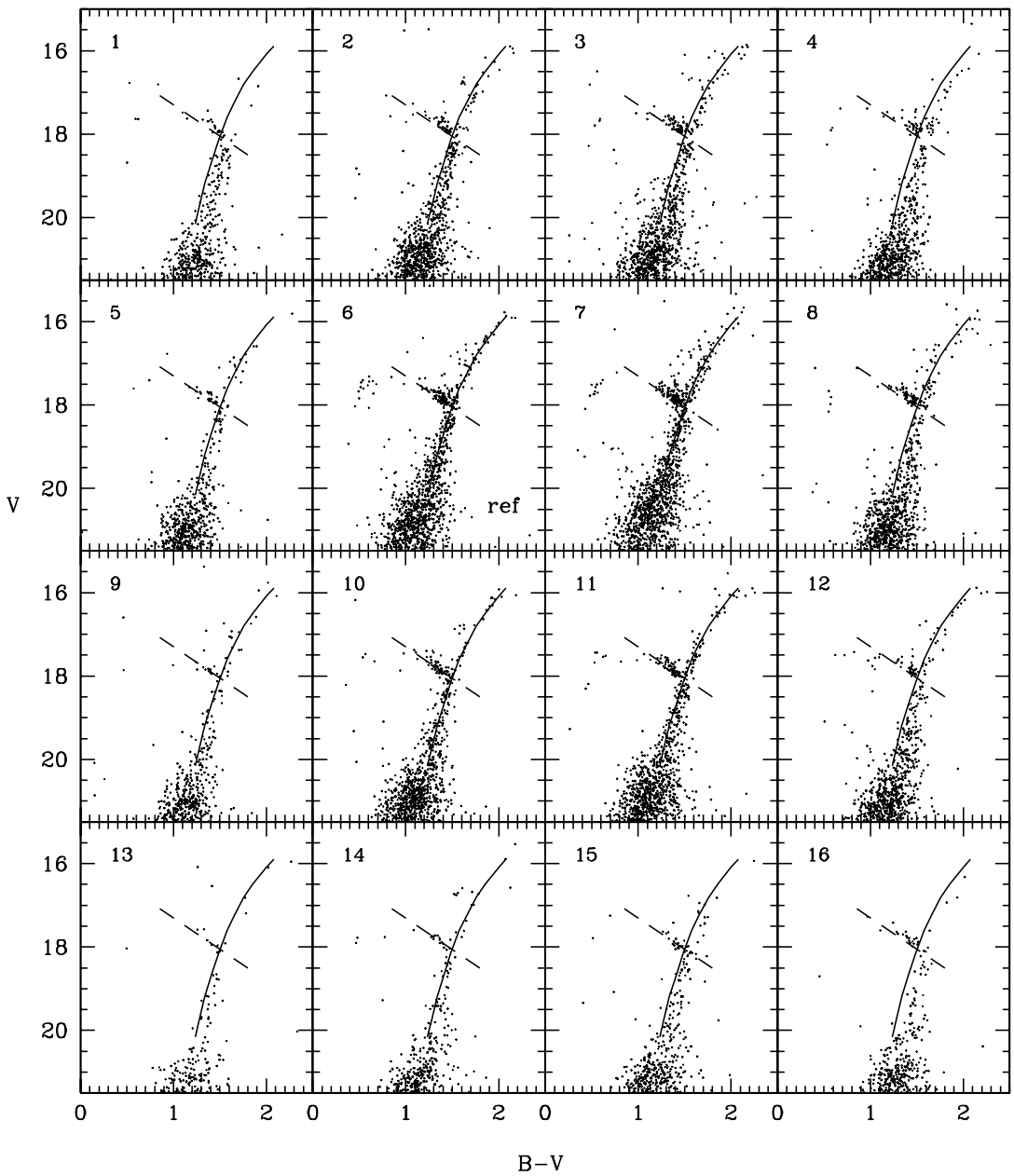

FIG. 7.—CM diagrams in 16 areas ($9''.1 \times 9''.1$) of the planetary-camera subimage of NGC 6441. The RGB ridge line (*solid line*) of the reference diagram in box 6 is overplotted on the other diagrams. The dashed line in each subimage is sloped as $dV/d(B-V) = 1.5$.

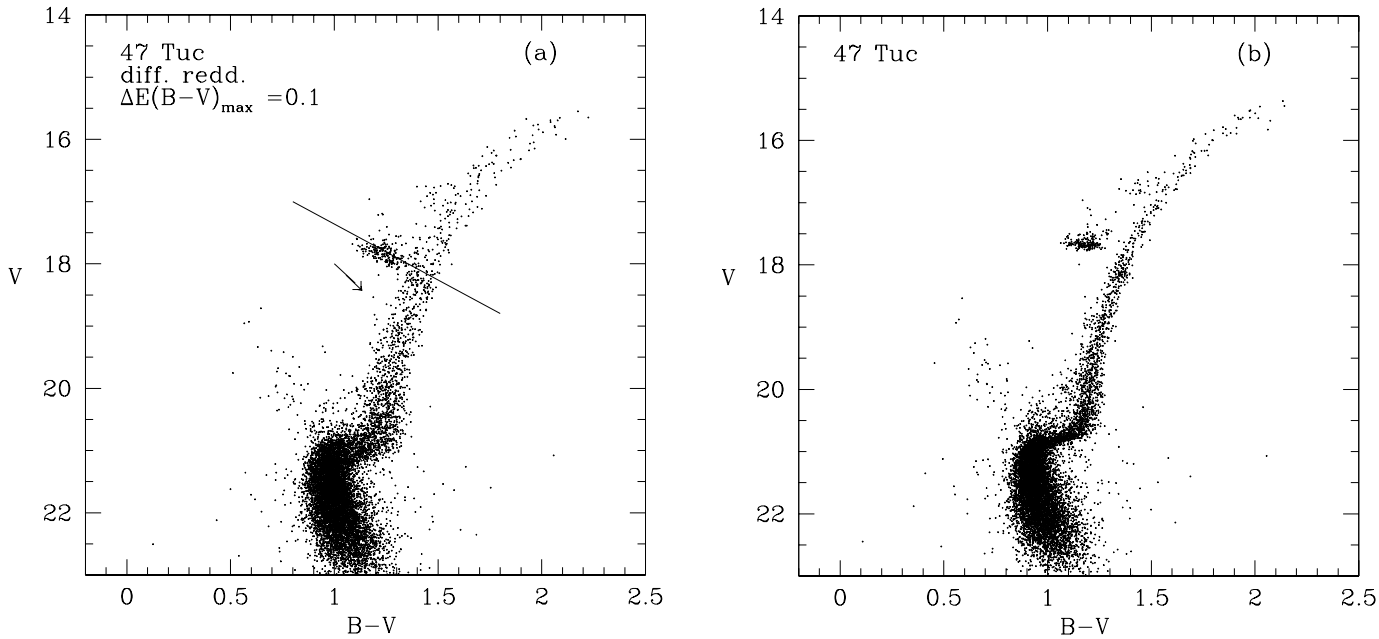

FIG. 8.—(*a*) CM diagram of 47 Tuc arbitrarily shifted by 3.6 mag in V and 0.38 mag in $B-V$ to match the NGC 6441 diagram, with an artificial differential reddening (see text for more details). The plotted arrow represents the slope of the reddening vector (Cardelli, Clayton, & Mathis 1989), and the solid line is drawn by assuming a slope of $dV/d(B-V) = 1.5$. (*b*) Original CM diagram of 47 Tuc.

Inspection of data in Figure 7 reveals indeed some relevant features. As a first point, one finds clear evidence for the occurrence of rather strong reddening differences, as disclosed, e.g., by the extreme case of area 4, in which the CM diagram shows a color shift as large as about $\Delta(B-V) \approx 0.15$ mag with respect to the reference diagram. This result is in good agreement with the maximum differential reddening estimated by Heitsch & Richtler (1999) from ground-based observations of the same cluster.

Moreover, the reference diagram shows a narrow RG sequence, suggesting that the observed width of the cluster RGB could be just an artifact of differential reddening across the cluster. If this is the case, this feature together with the presence of the blue tail provides a further constraint against the hypothesis of a spread of metallicity in the cluster stars.

A differential reddening of $\Delta E(B-V) \sim 0.1$ appears large enough to produce the observed redward slope of the HB. To substantiate such a scenario, we performed a numerical experiment, applying a random differential reddening by $\Delta E(B-V)_{\max} = 0.1$ to the observed CM diagram of 47 Tuc in such a way as to reproduce the color dispersion observed in the RGB of NGC 6441. The result of this experiment, as presented in Figure 8, shows the impressive similarity between NGC 6441 (Fig. 4) and the " reddened " 47 Tuc. As a relevant point, neither in NGC 6441 nor in the reddened 47 Tuc is the HB slope exactly along the adopted reddening vector. This occurrence is the natural consequence of randomly reddening an HB that is less sloped than the reddening vector. To get the maximum change in slope, one should apply the minimum amount of reddening to the hotter red HB stars and a larger amount to the cooler red HB stars. Thus, no matter how one builds up the HB in this way, the resulting slope of the lower envelope will be less than that of the reddening vector.

While differential reddening *could* convert a 47 Tuc–like HB into one such as the red HB of NGC 6441, it turns out that is not the case. To see this, one can note the thin RGB [$\Delta(B-V) < 0.1$ mag] shown by the reference diagram 6 in Figure 7 (but see also diagrams 5, 10, 13, and 14). This shows that there is not substantial differential reddening within those subsamples. However, one sees that the red HB in the same diagram is clearly sloping down with increasing $B-V$ color. Indeed, the HB in each subsample has a slope consistent with that of the global sample. Since the slope of each subsample is already fairly large, differential reddening will stretch the HB without substantially changing the slope. Since the large slope is even present in a subsample with small differential reddening, it must result from a real behavior of cluster HB stars.

Finally, let us note that by applying the same analysis to the *HST* Wide Field Planetary Camera 2 (WFPC2) observation of NGC 6388, we derive results on the differential reddening that are consistent with the previous discussion on NGC 6441.

5. FINAL REMARKS

Heitsch & Richtler (1999) have presented new photometry for five globular clusters in the inner Galaxy, concluding that differential reddening is indeed responsible for the sloped red HB morphologies at least in the case of NGC 5927. However, we have already advanced the suggestion of a real slope at least in NGC 6441. An inspection of the CM diagrams for the metal-rich globulars in the Padova *HST* snapshot database (G. Piotto et al., in preparation) plotted in Figure 9[8] reveals that all the clusters more metal rich than 47 Tuc except for NGC 6624 show red HB stars with a slope close to $dV/d(B-V) = 1.5$, indicated by the solid line. As for NGC 6624, the best agreement is reached with the dot-

[8] Harris (1996) (Fig. 9 legend) is also available on-line at http://physun.physics.mcmaster.ca/Globular.html.

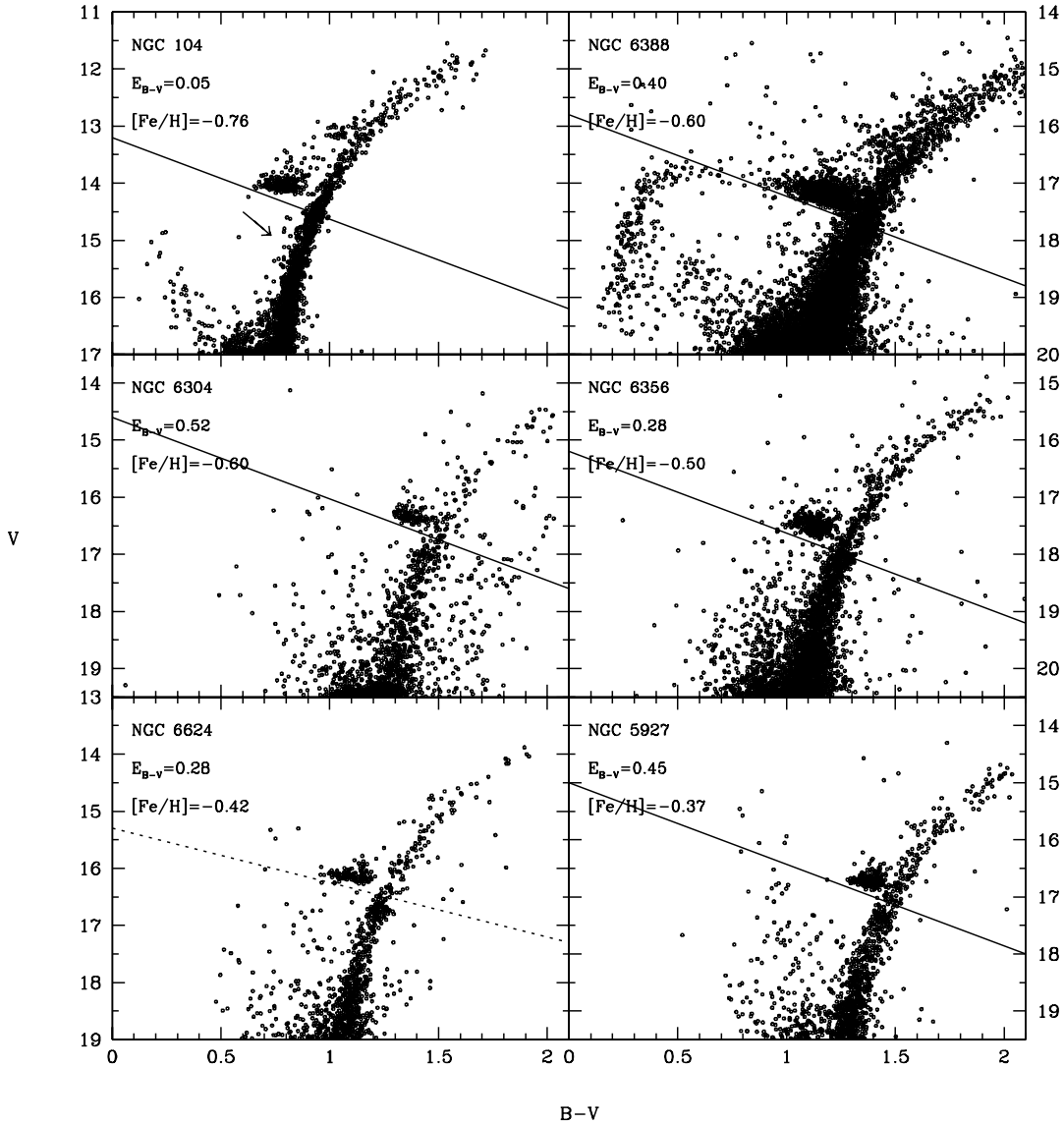

FIG. 9.—HBs of six well-populated clusters in the G. Piotto et al. (in preparation) database. The solid line is drawn by assuming a slope of $dV/d(B-V) = 1.5$ and the dotted one by $dV/d(B-V) = 1.0$ (see text). The arrow in the top left panel is the reddening vector ($R_V = 3.1$). Metallicity and reddening are from Harris (1996).

ted line, for a slope of the order of $dV/d(B-V) = 1.0$. Note that a similar slope can be clearly detected in the beautiful (V, $V-I$) color-magnitude diagram recently presented by Heasley et al. (2000). The HB of 47 Tuc has a shallow slope, close to the $dV/d(B-V) = 0.2$ expected from the theoretical models.

Since all the clusters with sloping HB also have a substantial amount of reddening, it appears difficult to ascertain the role of possible differential reddening. In this context, the reduced slope in NGC 6624 could have originated either from a smaller differential reddening or from a smaller metallicity ([Fe/H] $= -0.63 \pm 0.09$), as recently discussed by Heasley et al. (2000). However, the evidence for a sloping red HB in clusters such as NGC 6356 or NGC 6624, with a rather well-defined RG sequence, suggests that the sloping red HB is a real feature of metal-rich clusters. If this is the case, one should conclude that sloping HBs *are not necessarily correlated with the occurrence of blue tails*.

Comparison with theoretical predictions in the previous Figure 2 shows that such a slope can be attained by theoretical models only for the shorter mixing-length value we already regarded as largely improbable. If this slope is due to intrinsic properties of HB stars, one should conclude that the observations tell us that when the increasing metallicity pushes the HB at larger $B-V$ colors, then the red HB slopes down for unknown reasons. One would naturally account for such an occurrence by increasing the dependence of the bolometric correction on the temperature, but by an amount that is believed to be beyond current uncertainties. Therefore, this remains an open question requiring further investigation.

In this context, one should finally notice that current theoretical procedures adopted in producing HB models start with equilibrium ZAHB models that neglect all the phases of pre-HB evolution as well as the phases of readjustment of CNO elements across the H-burning shell (see, e.g., Castel-

lani, Chieffi, & Pulone 1989). The point is to understand if a pre-ZAHB evolution can play a role in the observed HB morphologies. However, a close inspection of the recent models performed to follow the evolution through the He flash by Brown et al. (2001) and preliminary computations by L. Piersanti (2001, private communication) do not support such a possibility.

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REFERENCES

Bell, R. A., & Gustafsson, B. 1989, MNRAS, 236, 653
Bono, G., Caputo, F., Cassisi, S., Castellani, V., & Marconi, M. 1997, ApJ, 489, 822
Borissova, J., Catelan, M., Ferraro, F. R., Spassova, N. Buonanno, R., Iannicola, G., Richtler, T., & Sweigart, A. V. 1999, A&A, 343, 813
Brocato, E., Castellani, V., Raimondo, G., & Walker, A. R. 1999, ApJ, 527, 230 (Paper I)
Brocato, E., Castellani, V., Scotti, G. A., Saviane, I., Piotto, G., & Ferraro, F. R. 1998, A&A, 335, 929
Brown, T. M., Sweigart, A. V., Lanz, T., Landsman, W. B., & Hubeny, I. 2001, ApJ, 562, 368
Caloi, V., Castellani, V., & Tornambé, A. 1978, A&AS, 33, 169
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Cassisi, S., Castellani, V., Degl'Innocenti, S., Salaris, M., & Weiss, A. 1999, A&AS, 134, 103
Cassisi, S., Castellani, V., Degl'Innocenti, S., & Weiss, A. 1998, A&AS, 129, 267
Castellani, V., Chieffi, A., & Pulone, L. 1989, ApJ, 344, 239
Castellani, V., Ciacio, F., Degl'Innocenti, S., & Fiorentini, G. 1997, A&A, 322, 801
Castelli, F., Gratton, R. G., & Kurucz, R. L. 1997, A&A, 318, 841
Chaboyer, B., Demarque, P., Kernan, P. J., & Krauss, L. M. 1998, ApJ, 494, 96
Dorman, B., Rood, R. T., & O'Connel, R. W. 1993, ApJ, 419, 596
Fagotto, F., Bressan, A., Bertelli, G., & Chiosi, C. 1994, A&AS, 105, 29
Fernandes, J., Lebreton, Y., Baglin, A., & Morel, P. 1998, A&A, 338, 455
Girardi, L., Bressan, A., Bertelli, G., & Chiosi, C. 2000, A&AS, 141, 371
Gratton, R. G., Fusi Pecci, F., Carretta, E., Clementini, G., Corsi, C. E., & Lattanzi, M. G. 1997, ApJ, 491, 749
Harris, W. E. 1996, AJ, 112, 1487
Heasley, J. N., Janes, K. A., Zinn, R., Demarque, P., Da Costa, G. S., & Christian, C. A. 2000, AJ, 120, 879
Heitsch, F., & Richtler, T. 1999, A&A, 347, 455
Horch, E., Demarque, P., & Pinsonneault, M. 1992, ApJ, 388, L53
Hubbard, W. B., & Lampe, M. 1969, ApJS, 18, 297
Itoh, N., Mitake, S., Iyetomi, H., & Ichimaru, S. 1983, ApJ, 273, 774
Layden, A. C., Ritter, L. A., Welch, D. L., & Webb, T. M. A. 1999, AJ, 117, 1313
Moehler, S., Sweigart, A. V., & Catelan, M. 1999, A&A, 351, 519
Ortolani, S., Momany, Y., Barbuy, B., Bica, E., & Catelan, M. 2000, A&A, 362, 953
Peimbert, M. 1995, in The Light Element Abundances, ed. P. Crane (Berlin: Springer), 165
Piotto, G., Sosin, C., King, I. R., Djorgovski, S. G., Rich, R. M., Dorman, B., Renzini, A., Phinney, S., & Liebertet, J. 1997, in Advances in Stellar Evolution, ed. R. T. Rood & A. Renzini (New York: Cambridge Univ. Press), 84
Pritzl, B., Smith, H. A., Catelan, M., & Sweigart, A. V. 2001, AJ, 122, 2600
Rich, R. M., et al. 1997, ApJ, 484, L25
Rogers, F. J., Swenson, F. J., & Iglesias, C. A. 1996, ApJ, 456, 902
Salaris, M., & Weiss, A. 1997, A&A, 327, 107
Sweigart, A. V. 2002, Highlights Astron., 12, in press (astro-ph/0103133)
Sweigart, A. V., & Catelan, M. 1998, ApJ, 501, L63
VandenBerg, D. A. 1992, ApJ, 391, 685
VandenBerg, D. A., & Bell, R. A. 1985, ApJS, 58, 561
VandenBerg, D. A., Swenson, F. J., Rogers, F. J., Iglesias, C. A., & Alexander, D. R. 2000, ApJ, 532, 430
Walker, A. R. 1998, AJ, 116, 220
Yi, S., Demarque, P., & Kim, Y.-C. 1997, ApJ, 482, 677
Zoccali, M., Cassisi, S., Bono, G., Piotto, G., Rich, R. M., & Djorgovski, S. G. 2000, ApJ, 538, 289
Zoccali, M., Cassisi, S., Piotto, G., Bono, G., & Salaris, M. 1999, ApJ, 518, L49