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A NEW FEATURE ALONG THE EXTENDED BLUE HORIZONTAL BRANCH OF NGC 6752[1]

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ABSTRACT

In this Letter, we report on the detection of a new feature in the complex structure of the horizontal branch (HB) of the Galactic globular cluster NGC 6752. In the U versus $(U-V)$-plane, the HB shows a discontinuity ("jump") at $U-V \simeq -1.0$ (corresponding $T_{\rm eff} \sim 23{,}000$ K). This "second U-jump" adds to the u-jump identified by F. Grundahl et al. in a dozen clusters at $T_{\rm eff} \sim 11{,}500$ K. We show that this new discontinuity might be due to the combination of post–zero-age HB evolution and diffusion effects. We identify 11 asymptotic giant branch manqué stars. The comparison between post-HB star counts and evolutionary lifetimes, as predicted by canonical stellar models, shows good agreement, at variance with similar estimates for NGC 6752 available in the literature.

Subject headings: globular clusters: individual (NGC 6752) — stars: evolution — stars: horizontal-branch — stars: low-mass, brown dwarfs

1. INTRODUCTION

Although the global properties of horizontal-branch (HB) stars in Galactic globular clusters (GCs) are rather well known, our current understanding of these objects is still challenged by several puzzling features that came out from a number of observations. Among these we mention (1) a nonmonotonic correlation between the HB morphology and metal abundance; i.e., besides metallicity (first parameter) there must be a "second" parameter (Sandage & Wildey 1967), or a combination of various parameters (Fusi Pecci et al. 1993), that determines the observed HB morphologies; (2) the HB is not homogeneously populated, and, in particular, all the HBs with blue tails (BTs) show the presence of gaps, i.e., regions significantly underpopulated by stars (Sosin et al. 1997; Ferraro et al. 1998; Piotto et al. 1999); (3) a fraction of the HBs with BTs are populated by the so-called extreme (or extended) HB (EHB) objects, i.e., hot HB stars reaching temperatures of 30,000 K or more (D'Cruz et al. 1996; Brown et al. 2001, hereafter B01), both in metal-poor and in metal-rich clusters (Rich et al. 1997); these objects are the GC counterpart of the field blue subdwarf population (Newell 1973); (4) all the HBs with BTs present a jump, i.e., a discontinuity around $T_{\rm eff} \sim 11{,}500$ K in the Strömgren (u, $u-y$) (Grundhal et al. 1999, hereafter G99) and Johnson (U, $U-V$) (Bedin et al. 2000, hereafter B00) color-magnitude diagrams (CMDs). Moreover, in some of the BTs there is evidence of (*a*) a discontinuity in the relative abundance of heavy elements (Behr et al. 1999), (*b*) a discontinuity in the surface gravities (Moehler et al. 2000), and, finally, (*c*) a discontinuity in the stellar rotation velocities (Behr, Cohen, & McCarthy 2000; Recio-Blanco et al. 2002). The abundance anomalies, the u-jump, and the discontinuity in the ($\log g$, $\log T_{\rm eff}$)-plane have been interpreted as different manifestations of the same physical phenomenon, i.e., the appearance of radiative metal levitation (G99), although Moehler et al. (2000) point out that this mechanism can only partly account for the low-gravity problem. Recio-Blanco et al. (2002) have also shown that the discontinuity in the rotation velocity might be related to the G99 jump.

Considerable attention (Landsman et al. 1996, hereafter L96; Sweigart 1997; D'Cruz et al. 2000; B01) has been devoted also to the EHB stars, because they still represent a challenge to canonical HB models (D'Cruz et al. 1996; B01) and also because they are suspected to be the principal sources of the ultraviolet emission in the so-called UV-upturn galaxies (Greggio & Renzini 1990). To shed more light on the origin of EHB stars, our group has undertaken a long-term project to obtain multiwavelength data of both the inner core and the outskirts of a number of EHB clusters. Our main goal is twofold: (1) to constrain the main properties of EHB stars and (2) to investigate the role of the dynamical evolution on the origin of these objects (B00).

In this Letter, we present preliminary results on one of the prototype EHB clusters, namely, NGC 6752. This object is a nearby [$(m-M)_0 = 13.05$; Renzini et al. 1996], low-reddening ($E_{B-V} = 0.04$; Penny & Dickens 1986), intermediate-metallicity ([Fe/H] $= -1.64$) cluster, with a complex HB extending to $T_{\rm eff} \sim 32{,}000$ K. We show that the HB of NGC 6752 presents a new interesting feature, located at $T_{\rm eff} \sim 23{,}000$ K, resembling the G99 u-jump. We discuss whether the current theoretical framework accounts for this "second jump." We also identify post-HB stars and compare their number with current evolutionary timescales.

2. OBSERVATIONS AND DATA REDUCTIONS

Images of NGC 6752 through U, B, and V filters were taken on 2000 July 25–26, with the Wide-Field Imager (WFI) at the 2.2 m ESO-MPI telescope at La Silla, Chile. The WFI camera consists of eight 2048 × 4096 EEV CCDs, with a total field of view of 34 × 33 arcmin^2. The exposure times (30 and 150 s in U, 5 and 10 s in B, and 3 and 7 s in V) were chosen in order to sample both the bright red giant branch (RGB) and the faint main-sequence stars. Weather conditions were photometric, with good seeing (below 0$''$.8 for all images). Basic reductions of the CCD mosaic were performed using the IRAF package MSCRED (Valdes 1998), while stellar photometry was performed using the DAOPHOT and ALLFRAME programs (Stetson 1994). Finally, instrumental magnitudes were calibrated to the UBV standard system on a chip-to-chip basis using a set of standard stars from Landolt (1992).

[1] Based on observations with the ESO/MPI 2.2 m telescope, located at the La Silla Observatory, Chile.

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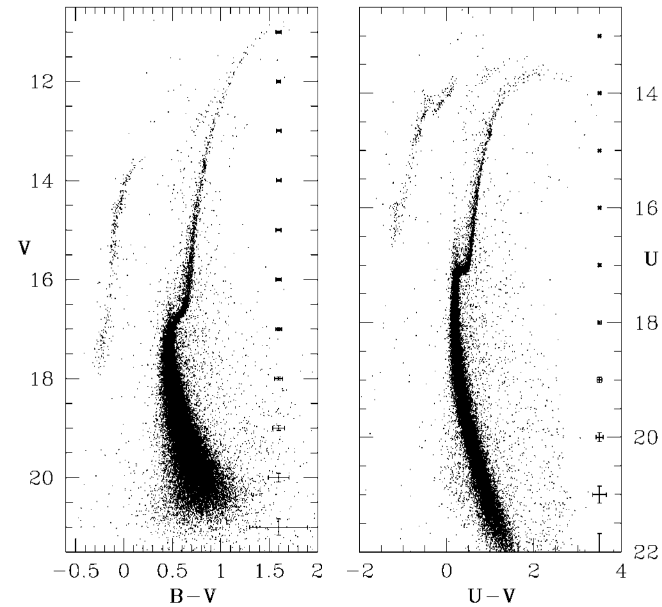

FIG. 1.—(V, $B-V$) and (U, $U-V$) CMDs for stars with $0'.3 < R < 13'.9$, where R is the projected distance from the cluster center. Photometric errors, as calculated by ALLFRAME, are shown on the right side of the two CMDs.

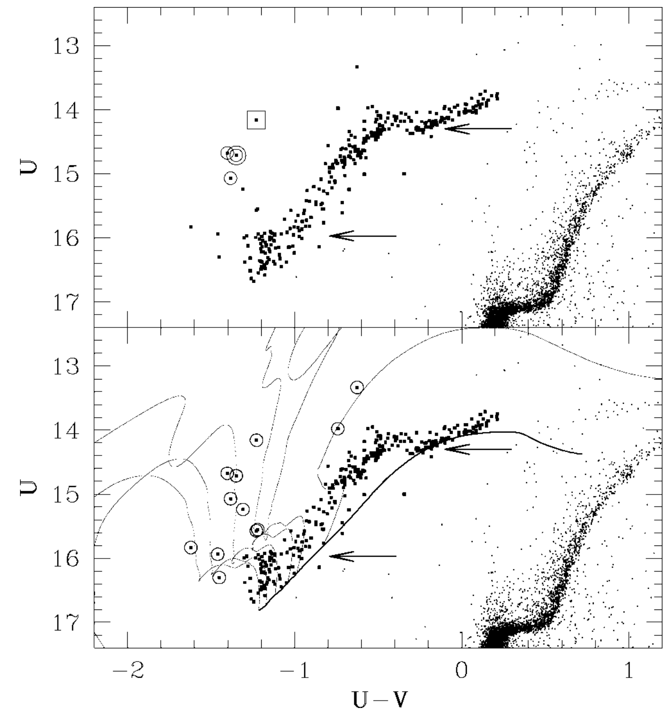

FIG. 2.—*Upper panel*: Close look at the jumps in the HB of NGC 6752. The four open circles are post-HB stars from Moehler et al. (1998), while the open square shows the star UIT1 of L96. *Lower panel*: The same diagram with a canonical $Z = 0.0006$ ZAHB model (*thick line*). Thin lines are HB models for stars with masses $M = 0.504$, 0.505, 0.510, 0.515, 0.520, and 0.540 $M_{\odot}$. Open circles are the 13 post-HB candidates.

3. THE COLOR-MAGNITUDE DIAGRAMS

Figure 1 shows the (V, $B-V$) and (U, $U-V$) CMDs for stars with $0'.3 < R < 13'.9$, where R is the projected distance from the cluster center. All the sequences of the CMD, from below the turnoff up to the RGB tip, are well defined and populated. The CMD shows an extended HB, which spans more than 4.5 mag in V and extends down to $V = 17.9$, i.e., ~1.5 mag below the turnoff. The HB does not show any new feature in the (V, $B-V$)-plane (Fig. 1, *left panel*), apart from the gap at $B-V = 0$ and $V = 14.2$ (Caloi 1999) and a sudden increase in the photometric dispersion below $V = 17$ that cannot be explained in terms of photometric errors alone. The HB itself is not homogeneously populated, with a clear underabundance of stars in the interval $17.0 \leq V \leq 15.7$.

It is surely more instructive to look at the (U, $U-V$) CMD (Fig. 1, *right panel*; see also the zoomed version in Fig. 2, *upper panel*). In this plane, the distribution of HB stars is remarkably discontinuous. In particular, (1) We note a *jump* in the stellar distribution at $U-V \sim -0.30$. This jump is analogous to the jump identified by B00 in the same bands in NGC 2808 and corresponds to the G99 jump. (2) Most interestingly, at $U \sim 15.9$, $U-V \sim -1.0$ there is a second jump in the distribution of the stars along the HB. This feature has never been identified, although, a posteriori, a similar jump can be seen in the CMDs of M13 and NGC 6752 in G99, and, to a lesser extent, in the CMD of NGC 2808 of B00. The larger photometric dispersion and the smaller sample of G99 and B00 partly mask this feature in their CMDs. (3) There are 13 stars significantly bluer and brighter than the bulk of HB stars (plotted as open circles in Fig. 2, *lower panel*). Most of them are the progeny of EHB stars.

Before turning our attention to the newly identified second jump, we briefly comment on the post-HB candidates. The evolution of extreme HB stars and their progeny have received special attention from the community, since they are crucial to understanding the spectral energy distribution (SED) of hot stellar populations in metal-poor and metal-rich stellar systems. In particular, we are interested in testing whether predicted evolutionary lifetimes are supported by empirical data since they have a significant impact on the SED of hot stellar populations. Previous investigation of NGC 6752 from Ultraviolet Imaging Telescope images (L96) showed a deficiency of a factor of 3 in the observed number of post-EHB stars with respect to the theoretical predictions. In Figure 2, there are 13 post-HB candidates. Four stars (circles in Fig. 2, *upper panel*) have been classified as post-EHB (asymptotic giant branch [AGB] manqué) stars by Moehler, Landsman, & Napiwotzki (1998). Note that the stars B852 and B4380 (Fig. 2, *double open circle*) in Moehler et al. (1998) share almost identical magnitudes and colors in our catalog. A fifth post-HB candidate has been proposed by L96 (UIT1 in L96; Fig. 2, *open square*), and we confirm their result.

Figure 2 (*lower panel*) shows the comparison in the (U, $U-V$)-plane between the observed CMD and He-burning evolutionary models. The thick line shows the zero-age horizontal branch (ZAHB), while the thin lines display the off-ZAHB evolution of selected AGB manqué and post–early-AGB structures (Greggio & Renzini 1990). Evolutionary computations have been performed by adopting an initial He content of $Y = 0.23$ and a metallicity $Z = 0.0006$. The ZAHB models were computed by adopting the He core mass and He surface abundance given by an RGB progenitor with mass equal to 0.8 $M_{\odot}$. These models were constructed by neglecting atomic diffusion and radiative levitation (see Cassisi & Salaris 1997 for more details). The transformation to the observational plane was done by adopting the bolometric corrections and the color-temperature relations by Castelli, Gratton, & Kurucz (1997). The comparison of the observed CMD with the set of models in Figure 2 allows us to isolate the HB stars that, after the end of the central He-burning phase, will eventually evolve into AGB manqué structures. The

$M = 0.520\ M_\odot$ model is the coolest model able to produce AGB manqué stars. In Figure 2, there are 84 HB stars hotter than this track; only 11 of the 13 post-HB stars can be classified as AGB manqué. The ratio between the two populations is 0.13, and it is consistent, within the uncertainties, with the predicted value of ∼0.09, thus solving the discrepancy pointed out by L96. The 11 post-HB stars have been inspected by eye, one by one. Apart from one case, there are no obvious blends or CCD artifacts that could cause large photometric errors. We believe that the much higher resolution of our data can explain the difference in the number of post-HB stars identified in the two works.

4. THE SECOND JUMP

The most intriguing feature in the CMDs of Figures 1 and 2 is the presence of the second jump around $U-V \approx -1.0$. The two arrows in Figure 2 mark the position of the two jumps along the HB blue tail. The comparison with the models in Figure 2 shows that the two jumps are located at $T_{\rm eff} \sim 11{,}600$ K and $T_{\rm eff} \sim 23{,}000$ K. The cooler part of the CMD is well reproduced by the models, but HB stars hotter than $T_{\rm eff} > 11{,}600$ K are systematically brighter than predicted by ZAHB models. However, the observed HB stars are steadily approaching the theoretical ZAHB when moving from $T_{\rm eff} \sim 11{,}600$ K to $T_{\rm eff} \sim 23{,}000$ K, where the second jump suddenly appears.

Figure 2 shows that the HB extends to $U = 16.8$, corresponding to a temperature $T_{\rm eff} \sim 32{,}000$ K. We can therefore exclude the possibility that the second jump is related to the presence of late helium flashers with envelope mixing (B01), as these stars are expected to be hotter than $T_{\rm eff} \sim 32{,}000$ K. Another possible explanation for the origin of the second jump could be related to the presence of binaries in the EHB stars of NGC 6752 (Peterson et al. 2002). Unresolved, equal mass binaries would appear brighter than single stars with the same temperature and luminosity, and this would mimic the observed second jump. However, the second jump in the HB would imply a rather ad hoc binary distribution along the HB.

Figures 2 and 3 show that the evolutionary path of hot HB stars is almost vertical in the (U, $U-V$)-plane, while the ZAHB is not. It is interesting to investigate whether the second jump can be an artifact of post-HB evolution in the photometric plane of Figures 2 and 3. To this purpose, we have calculated the post-ZAHB evolutionary times for stars hotter than $T_{\rm eff} = 23{,}000$ K. We find that He-burning stars evolving from the ZAHB should spend 40% of their time at magnitudes $U > 16.3$ and about 50% of their time at $15.8 \le U \le 16.3$. The ratio between these two lifetimes is 0.8. On the other hand, we count 15 stars in the lower box of Figure 3, and 30 stars in the upper box, to which we should add three more stars on the blue side of the upper box, which are very likely objects that started their post-ZAHB evolution from the lower box. The observed ratio is 0.46 ± 0.20. Therefore, the stellar distribution in the hottest portion of the HB in NGC 6752 cannot be due *only* to the peculiar morphology of evolutionary tracks in the (U, $U-V$)-plane. Moreover, if we interpret all the stars in the two boxes of Figure 3 simply as HB stars evolving from the ZAHB as expected from the canonical models, we are faced with a further anomaly: a sharp peak in the distribution of stellar masses. According to the models, all the stars with $T_{\rm eff} > 23{,}000$ K have a mass of $0.505\ M_\odot$, with a dispersion of only $0.003\ M_\odot$. It is difficult to understand the origin of such a peculiar distribution along the HB.

Since the stellar distribution across the hotter second jump resembles the G99 jump, one might wonder whether both features share similar physical origins. The occurrence of the G99 jump was explained as the aftermath of radiative levitation that causes a substantial increase in the metal content of the outermost layers. This finding confirms earlier results by Glaspey et al. (1989) in NGC 6752 and later investigations by Behr et al. (1999, 2000) for a few other clusters. Both groups find that hot HB stars present He depletion and a remarkable overabundances of heavy elements (Fe, Ti, N, P, etc.) when compared with the cluster abundances. In particular, in NGC 6752, Glaspey et al. (1989) found an overabundance of iron by a factor of 50 (and He depletion) in the star CL 1083 ($T_{\rm eff} = 16{,}000$ K). Instead, no abundance anomalies were found in the star CL 1007 with $T_{\rm eff} = 10{,}000$ K. The results by Moehler et al. (2000), who find strong He underabundances also for stars with $T_{\rm eff} > 23{,}000$ K, suggest that diffusion is present in the hottest stars and might be related to the second jump anomaly.

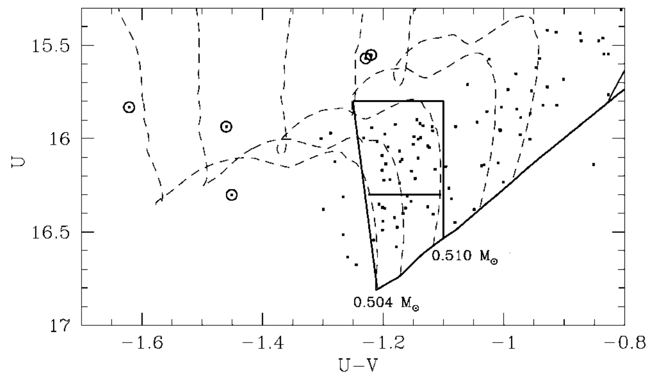

FIG. 3.—Same as Fig. 2, but zooming around the EHB

Radiative levitation and diffusion are possible after the disappearance of the envelope convective layers located across the H and He I ionization regions, at $T_{\rm eff} \sim 10{,}000$–$11{,}000$ K (Caloi 1999; Sweigart 2000). For $T_{\rm eff} > 11{,}000$ K, radiative levitation takes place in a thin radiative layer located between the surface and the second He ionization region (He II). When moving toward hotter effective temperatures, the radiative layer becomes thinner, since the increase in the effective temperature causes a systematic shift of the He II region toward the surface (Sweigart 2000). Canonical stellar models predict that the He II convective region approaches the stellar surface in the ZAHB structures at $T_{\rm eff} \sim 23{,}000$ K. In addition, as expected on theoretical grounds (Vink & Cassisi 2002), the mass-loss efficiency increases with effective temperature. Mass loss works as a competing process to diffusion (Michaud & Charland 1986), and indeed it decreases the efficiency of radiative levitation in producing large chemical overabundances of heavy elements. As a result, radiative levitation is less and less effective in the effective temperature range $T_{\rm eff} \sim 11{,}000$–$23{,}000$ K, and the stars should steadily approach the canonical ZAHB luminosity, when moving toward hotter HB stars. This evidence is supported by the observed HBs (Fig. 2). At the same time, the overabundance of heavy elements should decrease as well. Unfortunately, we still lack of observational data to support the latter hypothesis. For stars with $T_{\rm eff} > 23{,}000$ K, as a consequence of the larger surface gravity and longer central He-burning lifetime, one expects that the atomic diffusion becomes more and more efficient in decreasing the envelope He abundance, implying the quenching of the He II convection. At the same time, the large increase in the effective temperature should enhance the capability of radiative levitation in producing a chemical separation in the stellar envelope. According to this working scenario, HB stars with 22,000 K ≤

$T_{\rm eff} \leq 24{,}000$ K should present a change in the surface chemical composition in comparison to hotter and cooler structures. It is rather tempting to associate the second jump identified in this Letter with this discontinuity in the chemical composition. It is possibly the combination of this discontinuity and the off-ZAHB evolutionary path and timescales that produces the observed peculiar morphology of the hottest part of the HB in NGC 6752.

Even though this scenario is quite attractive, the results of Michaud, Vauclair, & Vauclair (1983, hereafter M83) could somewhat challenge it. By modeling the change in the chemical stratification caused by atomic diffusion and radiative levitation, they found that the He abundance in the envelope of hot HB stars sharply decreases in a very short timescale (see their Figs. 1 and 2). This effect is due to the high efficiency of atomic diffusion. In particular, their computations suggest that for structures located at $T_{\rm eff} \sim 20{,}000$ K, the He II convective zone should disappear after $\approx 10^4$ yr. If these predictions are correct, then our proposed scenario is ruled out. However, in the same investigation, M83 have qualitatively estimated also the effects of turbulent motions and found that if the convective transport is particularly efficient it could limit the efficiency of atomic diffusion. This means that He, and in turn the convective region in the envelope, should not rapidly disappear in extreme HB structures. This evidence is further supported by the fact that HB models constructed by M83 that neglect both the mass loss (see Unglaub & Bues 2001 for a detailed discussion) and the effects of turbulence predict He abundances lower than observed.

In order to estimate the minimum He abundance needed in the stellar envelope of hot HB stars to have an He II convection zone, we have computed several models for different assumptions on the external abundance of He. We have found that for an He abundance of $Y \approx 0.1$, the envelope of extreme HB structures still presents a very thin convective layer across the He II region. On the other hand, the spectroscopic investigation by Moehler et al. (2000) suggests that the He content in the EHB stars of NGC 6752 with 17,000 K $< T_{\rm eff} <$ 22,000 K is lower: $0.01 < Y < 0.08$, with an uncertainty of $\sim$0.02. However, to reach firm conclusions concerning the cutoff in the He abundance for the occurrence of a convective region, one needs a new generation of evolutionary models that consistently account for all physical mechanism(s) affecting the chemical stratification of HB stars.

Nevertheless, if the suggested scenario is actually at work, the presence of a convective region (very close to the surface in a narrow mass range in the EHB) would imply that the stars across the second jump, when compared with the stars across the first jump, should show larger macroturbulence velocities and a larger spread in chemical abundances. This qualitative scenario is somehow supported by spectroscopic measurements of field sdB and sdO stars. As a matter of fact, there is evidence that the He abundance steadily increases when moving from sdB to sdO. In these stars, a strong depletion of silicon and a mild underabundance of carbon (Lamontagne, Wesemael, & Fontaine 1987) have also been observed, while other elements are enriched even with respect to solar composition (Heber et al. 2002). Accurate abundance measurements of He and heavy elements along the hot portion of the HB in GCs, such as NGC 6752, could be crucial to constrain the theoretical framework. At the same time, new optical and UV spectroscopic data are needed to ascertain the occurrence and efficiency of mass loss among EHB stars (Heber et al. 2002).

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