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Ruminations on horizontal branch blue tails

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Abstract. Some globular cluster horizontal branches (HB) have long blue tails (BT), which in some cases extend to magnitudes fainter than the main sequence turnoff (MSTO). The origin of these BTs remains mysterious even after several decades of work. In this brief paper we offer no solutions but do address some issues of nomenclature and point out the problems of some photometric systems and virtues of others.

Key words. Stars: horizontal branch – Stars: globular cluster

1. Introduction

The concept of HB blue tails probably originated with the CMD of NGC 6752, which was presented by Russell Cannon at the 1973 Frascati globular cluster (GC) workshop but not published for many years. In visual CMDs of NGC 6752 (and many others to follow), the HB drops downward at high temperature often becoming an almost vertical sequence. This feature looked like a tail hanging from the horizontal part of the blue HB, hence the name. In a few massive GCs there is an apparent extension of the BT which is more properly called the blue hook (BHk; see below)

BT stars (excluding the BHk) are reasonably well described as HB stars which have very small hydrogen envelopes. Extreme mass loss either as single stars on the red giant branch or in interacting binaries is a factor. The latter may be important because the field analogs of BT stars are observed to have a large binary fraction. Enhanced envelope helium abundance, either primordial from an early burst of nucleosynthesis within the cluster or from dredge up at the helium flash, may play a role.

2. HB sub-population nomenclature

The HB is composed of helium-core/hydrogen-shell burning stars. The mass of the helium core is roughly constant along the HB, and the initial position of star along the HB is determined by the mass of the hydrogen rich envelope. The HB is traditionally split into red, variable, and blue (RHB, VHB, and BHB, respectively) sub-populations, depending on whether the stars are redder than, within, or bluer than, the RR Lyrae instability strip. It certainly does not do justice to true variety of BHB morphology to lump all of the clusters with a given fraction of BHB stars into a sin-

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gle class. There is considerable variety among those clusters with BTs.

Nomenclature for BTs is not standardized and is often used inconsistently. Rood & Crocker (1989), Fusi Pecci et al. (1993), and Recio-Blanco et al. (2006) have each suggested ways to measure BTs, and the fact that measures of BTness keep being invented demonstrates a lack of consensus on a definition of BTs. In addition to length, BTs typically have gaps which appear to divide them into sub-populations. Sub-populations, *extreme HB* (EHB) and blue hook (BHk) stars, are sometimes recognized within the observed BTs, even if without a precise observational definition.

The EHB population is theoretically well defined: EHB stars lie at the hottest extreme of the zero-age HB (ZAHB), and they do not return to the asymptotic giant branch (AGB), but rather spend their He-shell burning phase as hot AGB-manqué or Post-early AGB stars (e.g., Dorman et al. 1993). There is no comparably precise way to observationally select EHB stars. If far-UV (FUV) (e.g., *HST* F160W) photometry is available, detailed comparisons with stellar models can be made. These suggest that in a few clusters, the transition between BHB and EHB stars may be associated with a gap in the HB morphology (Ferraro et al. 1998).

The importance of EHB stars is also connected with the fact that they and their progeny are thought to be the source of the UV radiation excess observed in the integrated spectra of some elliptical galaxies (Dorman et al 1995; Yi et al. 1998), and one might be able, for example, to determine the age of the galaxy on the basis of its UV excess.

In a few clusters there is an additional population hotter and less luminous than the EHB stars. Following nomenclature used in recent studies, we call this population *Blue Hook* stars (BHk). In visual and even some UV (e.g., m_{255}, $m_{255} - m_{336}$) CMDs, BHk stars appear as fainter extension of the BT and are separated from the EHB population by a gap (e.g. Busso et al. 2007; Dalessandro et al. 2007). While the effective temperature $T_{\rm eff}$ of HB stars can be reasonably well determined

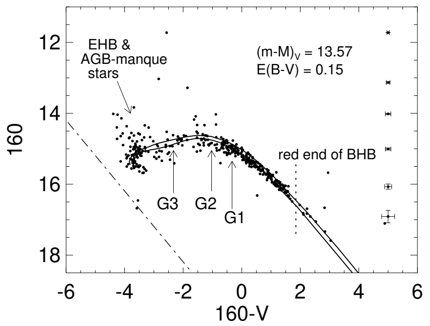

Fig. 1. The 160-V CMD of ω Cen from D'Cruz et al. (2000). The blue hook is apparent at the hot end of the HB. The gaps in the BHB distribution are marked with 'G' and are associated with similar gaps found in Ferraro et al. (1998)

from their position along the BT, it is not appropriate to extrapolate this to the BHk. Accurate stellar parameters for BHk stars require FUV photometry (e.g., see the BHk studies in ω Cen and NGC 2808, D'Cruz et al. 2000; Moehler et al. 2004). Indeed, it is only in FUV CMDs that the origin of the name "blue hook" becomes apparent (see Fig. 1). The nature of BHk stars is still a matter of debate. They may be related to the so-called late hot flashers (Moehler et al. 2004), or to high helium abundances (Busso et al. 2007).

3. The vertical structure of HB BTs

We have been intrigued by the distribution of stars *along* the HB since the idea of the *second parameter* problem was introduced by Sandage & Wildey (1967). Many things can affect the distribution of stars along the HB: cluster age, primordial helium abundace, helium mixed into the envelope along the red giant branch or at the helium flash, CNO abundance (C+N+O), etc. The trouble is that determining how any of these parameters affect HB morphology is inextricably linked to mass loss. There are three routes toward identifying parameter(s) which might lead to BTs: 1) adopting some mass loss formalism as a matter of faith; 2) searching for parameter variation elsewhere in the CMD; 3) establishing an empirical mass loss formula based on observations of cluster stars.

Relating to point 2), there is now compelling evidence for multiple populations in globular clusters (e.g., Piotto at this meeting and Piotto et al. 2005; D'Antona et al. 2005; Sollima et al. 2007). Multiple main sequences (MS) indicate discrete stellar populations with different helium abundances. Clearly the variation in MS helium will propagate into HB structure; *however,* one still must *make some assumption about mass loss* to determine what that HB structure will be. Concerning point 3), there has been some recent progress toward a new mass loss formula (Origlia et al. 2007, and this meeting).

One can attempt to dodge the mass loss issue by looking at the vertical structure of the HB. To relate to stellar models "vertical" must be a measure of $\log L$. Rood & Crocker (1989) and Crocker et al. (1988) (CRO) attempted to do this using the $\log g$, $\log T_{\rm eff}$ diagram and a $\mathcal{X}_{\rm HB}, \mathcal{Y}_{\rm HB}$ coordinate system. For BT stars $\mathcal{Y}_{\rm HB}$ determined from optical CMDs was not a good measure of $\log L$. Rood & Crocker (1989) actually schematically indicated how some currently popular BT parameters would affect the HB in $\log g$, $\log T_{\rm eff}$ diagrams. CRO presented some observational results. With late 80's technology sample size was limited and the tips of the BTs could not be explored at all. Still CRO found a very puzzling jump in $\log g$, which in retrospect we can recognize as the equivalent of the Strömgren u jump (see below). In the mid 1990's Moehler and her collaborators (among others) picked up the use of $\log g$, $\log T_{\rm eff}$ diagram and continue to use it effectively (e.g., Moehler et al. 1995; Moehler et al. 2004).

With the advent of HST and infrared detectors it became possible to do photometry at wavelengths from far ultraviolet to near infrared. By choosing an appropriate color-magnitude diagram (CMD) one could in principle measure luminosity. The vertical structure of the BHB could be explored using UV CMDs.

Dorman and Rood (unpublished) explored several BT clusters and were frustrated by their inability to fit observed HBs to models in multiple CMDs. The source of this problem turned out to be the Strömgren u jump found by Grundahl et al. (1998). BHB stars hotter than 11,500 K were brighter than canonical HB models in the u, $(u-y)$ CMD. Grundahl et al. (1999) showed that the jump occurred in all clusters where the hot part of the BHB was populated. Grundahl et al. (1999), supported by abundance measurements of Behr et al. (1999), argued that the u-jump arises because enhanced atmospheric opacity in the near UV due to the radiative levitation of some elements. This shifts light into the u filter bandpass. A similar jump should occur in U and HST $F336$. Someplace in the spectrum there should be a corresponding depression in the radiation, perhaps in HST-$F255$.

These shifts did not seem to affect $F160$ and UIT far-UV photometry and V (e.g., Rood

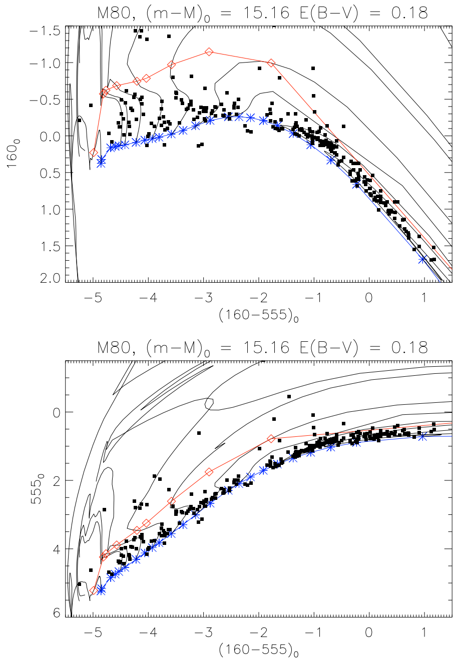

Fig. 2. (160, 160−555) and (555, 160−555) CMDs (555 ≈ V) for the BT cluster M80. The plots are based on data from Ferraro et al. (1998) and unpublished stellar models of Dorman. The lower line with $*$'s is the ZAHB; the upper line with $\diamond$'s marks the points on the evolutionary tracks where models have reached 90% of their core He burning age.

and Dorman, and Grundahl et al. 1999), so the 160, (160 – 555) and 555, (160 – 555) CMDs seem to be the best bets to explore the luminosity structure of the BHB. These plots for the GC M80 are shown in Fig. 2. A slight adjustment in distance modulus was made to match models to the redder HB in the 555, (160−555) CMD; such an adjustment can compensate for a mismatch in composition between the cluster and models or errors in input physics.

The fit to the hottest stars is also remarkably good. Some parameters like He variations produce BTs along with a change in HB luminosity; superficially these are ruled out. However, the good fit for the hotter stars could be fortuitous. The reddening for M80 is fairly large, so errors introduced via the reddening law could cancel changes in luminosity. We hope that nature is not so unkind.

The change track morphology can be seen at (160 – 555) ∼ −3.5; stars hotter than this should not return to the AGB, i.e., they are EHB stars. One should observe AGB-manqué stars in M80, and we do. The HB broadens in luminosity for (160 – 555) < −2 as expected from the models. Ultimately one might be able to test uncertain physics such as the treatment of the breathing pulse phenomenon (Dorman & Rood 1993) using a quantitative comparison between observations and models as shown here.

Fig. 3 shows the 336, (160 – 555) and 255, (160 – 555) CMDs for M80. As expected from the u-jump effect, the stars in the lower plot lie consistently above the ZAHB at all $T_{\rm eff}$. Grundahl et al. (1999) found that the size of the u-jump decreased at high $T_{\rm eff}$ both as measured using u or $\mathcal{Y}_{\rm HB}$. We conjecture that this results from the fact that both u and $\mathcal{Y}_{\rm HB}$ become poor measures of $\log L$ at high $T_{\rm eff}$, and that the u-jump effect continues to the hot end of the HB. The upper panel of Fig. 3 indicates that the flux in the 255 filter is depressed relative to the ZAHB, at least for the cooler stars. Similar plots for M13 and M79 do not show such an obvious shift, so this result should be taken as tentative.

Fig. 4 shows the (160, 160 – 555) CMDs for three BT clusters, M79, M80, and M13. As found by Ferraro et al. (1998), M13 is quite similar to M80; both have populated EHBs and AGB-manqué stars. On the other hand, the EHB of M79 is not populated and there are no AGB-manqué stars observed.

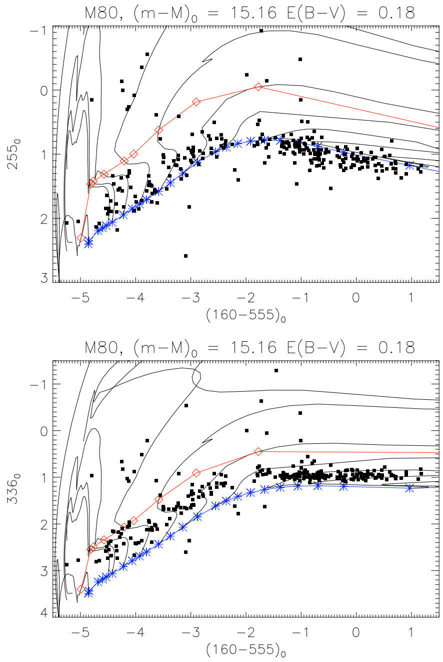

Fig. 3. (160, 160−555) and (555, 160−555) CMDs for M80.

4. Discussion

At this point the optimum CMD for the study of BT clusters appears to be the (160, 160 – 555) CMD. BHk and EHB stars can be easily identified. The length can be measured simply by the extent in (160 – 555). For comparison with HB models, CMDs involving u, $F336$, and U should be used with caution because of the u-jump effect. The same is probably true for CMDs involving $F255$. Unfortunately the often used 255, (255 – 336) CMD is probably optimally bad, with the u-jump entering 336 in one direction and 255 in the other leading to a double whammy in (255 – 336).

It is important to use the nomenclature BT, BHB, EHB, and BHk accurately. The connection of BHk stars to a small number of very

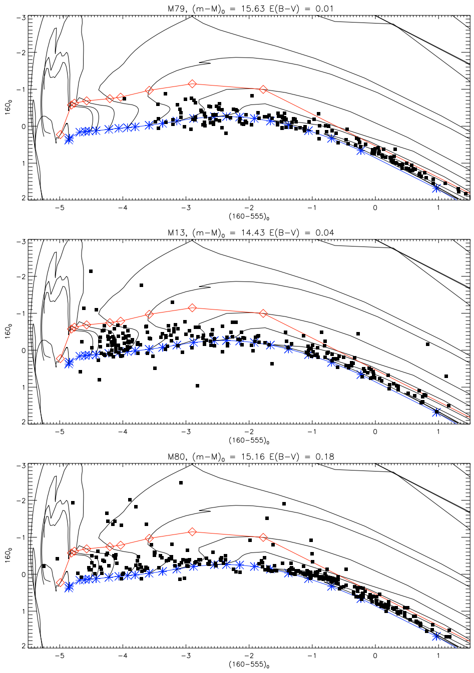

Fig. 4. (160, 160 − 555) CMDs for three BT clusters. Data for M13 and M80 from Ferraro et al. (1998); HST and GALEX data for M79 from Rood et al., in prep

massive clusters is perhaps the strongest correlation in the game of HB morphology. In searching for correlations between HB morphology and assorted parameters, the BHk clusters should be treated as a separate class.

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