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Multimodal horizontal branches: empirical evidence and possible evolutionary scenarios

M. Catelan

Pontificia Universidad Católica de Chile, Departamento de Astronomía y Astrofísica,
Av. Vicuña Mackenna 4860, 782-0436 Macul, Santiago, Chile
e-mail: mcatelan@astro.puc.cl

Abstract. We review the available empirical evidence for the presence of "gaps" and multimodal distributions among horizontal branch (HB) stars, along with some of the theoretical scenarios that have been proposed to explain these features. While gaps along the HB have become increasingly less prominent and frequent as more and better color-magnitude diagram data have been obtained for Galactic globular clusters, the evidence for multimodal HBs has instead become stronger. In addition, different HB modes have recently started to be traced down to multiple components that have been detected among subgiant branch and main sequence stars, thus suggesting that their origin lies in the complex physical processes that took place at the earliest stages in the history of massive stellar clusters.

Key words. Stars: Population II – stars: fundamental parameters – Hertzsprung-Russell diagram – Galaxy: globular clusters – Galaxy: stellar content

1. Introduction

"Gaps" and "multimodality" are two terms that one will invariably come across, when studying the literature that addresses the horizontal branch (HB) morphology of resolved globular star clusters (GCs). In this sense, it is instructive to review the following authoritative definitions of the key terms "gap" and "mode," as provided by the Cambridge dictionary:

Gap: *an empty space or opening in the middle of something or between two things*

Mode: *the number or value which appears most frequently in a particular set*

According to these definitions, a multimodal distribution may clearly exist *without* any gaps being present – all that is required, in this case, is for the probability distribution to present two or more statistically significant peaks. Indeed, as we shall soon see, the empirical evidence has increasingly been suggesting that "empty spaces" or "forbidden regions" do not actually exist along the HB. The evidence for HB multimodality, on the other hand, *is* becoming increasingly stronger, especially among some of the most massive globulars, driving renewed interest in theoretical interpretations of the observed features.

It is interesting to note that the first reported gaps on observed color-magnitude diagrams (CMDs) were not located on the HB, but rather either along the main sequence (MS) or the red giant branch (RGB) of both open (Mitchell & Johnson 1957; Eggen & Sandage 1964, 1969) and globular (Sandage, Katem, & Kristian 1968; Harris & Racine 1974) clusters.

Not all such gaps have withstood the test of time. In particular, RGB gaps, once viewed as a "major significant feature" (Sandage et al. 1968), were soon attacked on a statistical basis (Bahcall & Yahil 1972). Later, Renzini & Fusi Pecci (1988) pointed out that "the tendency has been for such gaps to get filled with increasing sample size"; it is indeed unusual for one to find recent CMD studies in which significant RGB gaps are claimed to be present. On the other hand, some of the gaps along the MSs of open clusters (the "Böhm-Vitense gaps"; Böhm-Vitense 1970; Böhm-Vitense & Canterna 1974) are still widely thought to be real (e.g., Rachford & Canterna 2000), and caused by the change in behavior of convection as a function of MS mass (D'Antona et al. 2002). Will any of the widely reported HB gaps similarly withstand the test of time, or will they share the same fate as the RGB gaps?

2. Gaps along the HB

Apparently the first HB gap to have been identified was that along the blue HB of M12 = NGC 6218 (Racine 1971). Racine, in addition, remarks that similar features may be present in several other globulars, including NGC 4147, M2 (NGC 7089), M13 (NGC 6205), M15 (NGC 7078), M22 (NGC 6656), and M92 (NGC 6341). In fact, it is quite curious that Sandage et al. (1968), while calling attention to what they termed "a major significant feature" (i.e., a gap) along the RGB of M15, should have missed the gap on the blue HB of the cluster, which was to be prominently emphasized (and thereafter to play quite an influential role in shaping ideas in this field) almost two decades later (Buonanno, Corsi, & Fusi Pecci 1985). HB gaps have become mainstream mainly after the work by Newell (1973) and Newell & Graham (1976), who identified two gaps along the color-color diagram of *field* blue HB stars, located at $T_{\rm eff} \simeq 12{,}900$ K and at $T_{\rm eff} \simeq 21{,}900$ K – the so-called *Newell gaps* 1 and 2, respectively – and by Newell & Sadler (1978), who identified a similar gap to Newell's gap 2 along the extended blue HB of NGC 6752, based on photometry by Cannon & Lee (1973, unpublished; see Fig. 3 in Lee & Cannon 1980 for their original NGC 6752 CMD). Subsequently, many other clusters have been claimed to show signs of gaps along the HB (see Catelan et al. 1998, for a review and extensive references). Are any such gaps real, and, if so, which?

It is very difficult to provide a conclusive answer to this question. At least some of the reported gaps will likely vanish, or at least become much less prominent, with increasing sample sizes, as in the case of the RGB gaps that historically preceded them. Such a tendency was already noted a decade ago by Catelan et al. (1998), who called attention to the fact that recent photometry has tended to cast doubt on the reality of at least some of the gaps which were originally reported to be present along the CMDs of GCs. As an example, we show, in Figure 1, a comparison between the NGC 288 CMD obtained by Buonanno et al. (1984) and the one obtained by Kaluzny (1996). The hotter of the two Newell gaps identified in NGC 6752 by Newell & Sadler (1978), which appeared as a 1 mag-wide void in the original CMD by Lee & Cannon (1980), has with time also proved not to be devoid of stars as originally thought, but rather a region of the CMD that simply appears to be more sparsely populated than its surroundings (Buonanno et al. 1986; Thompson et al. 1999): bona-fide, spectroscopically confirmed HB stars are indeed present in its interior (Moehler, Heber, & Rupprecht 1997).

Several authors, on the other hand, have suggested that HB gaps are not only ubiquitous in the CMDs of GCs, but in fact are also located at the same place (as defined by either $T_{\rm eff}$ or total mass) in all clusters (e.g., Ferraro et al. 1998; Caloi 1999; Piotto et al. 1999; Momany et al. 2004). However, it should be noted that there are several published, high-quality CMDs for GCs with well-developed blue HBs that reveal *no* obvious gaps of any sort. Figure 1 shows NGC 288 to be one such cluster – but other noteworthy cases

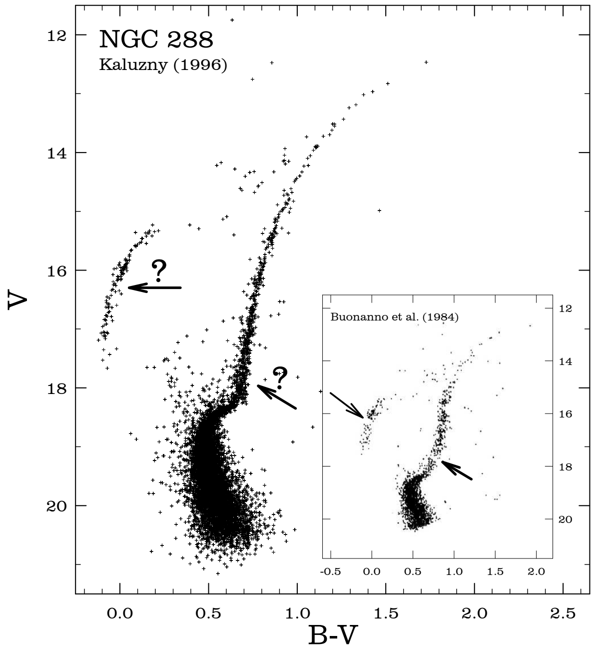

Fig. 1. Comparison of the recent NGC 288 CMD by Kaluzny (1996) with the original one by Buonanno et al. (1984, *inset*). Arrows indicate gaps in the 1984 CMD that appear to have vanished in the more recent of the two studies.

include M79 (NGC 1904; Dixon et al. 1996) and M2 (NGC 7089; Lee & Carney 1999). We conclude that much more extensive, high-precision, multi-band, wide-field photometric surveys of GCs will be needed before we are in a position to conclusively establish how commonplace HB gaps really are.

In addition to more extensive photometry, more robust statistical techniques are also required to test the reality of features (such as gaps) in the observed CMDs: as shown by Catelan et al. (1998), the widely employed recipes provided by Hawarden (1971) give misleading results, generally overestimating the statistical significance of the detected features.[1] Possibly a combination of the Bahcall & Yahil (1972) approach with the binomial formalism proposed by Catelan et al. could lead to more realistic results.

[1] As an example, Crocker, Rood, & O'Connell (1988) estimated, on the basis of the Buonanno et al. (1984) CMD, a 100% probability that the gap on the blue HB of NGC 288 was *not* a statistical fluctuation – which is clearly inconsistent with the evidence presented in Figure 1.

3. Whence the "Newell gaps"?

Behr (2003b) has recently carried out an extensive study of rotation velocities of field HB stars, and included 27 stars from the Newell (1973) and Newell & Graham (1976) samples. On the basis of high-resolution spectra obtained with the McDonald Observatory's 2.1m telescope, Behr concluded that *"fewer than half (11 of 27) of the Newell stars that we observed were clearly HB objects, with another 11 stars classified as Population I dwarfs, and the remaining five stars marked as pAGB [post-Asymptotic Giant Branch], subgiants, and such."* With such a contaminated sample, one cannot help but wonder "why would gaps appear in the color distribution of such a heterogeneous set of stars." In view of such evidence, another careful look at the data for field blue HB stars is clearly in order.

4. HB gaps and HB theory

Canonical HB theory does not predict any sharp transitions along the HB. Accordingly, gaps are not naturally predicted by theory, unless one assumes sharp discontinuities in envelope mass – or, equivalently, in the amount of mass loss among red giants (e.g., Rood 1998).

The suggested invariance in the position of certain HB gaps from one cluster to the next (Ferraro et al. 1998; Piotto et al. 1999), irrespective of [Fe/H] or central density, would require a fine tuning in the RGB mass loss process, since mass loss is expected to depend on both metallicity and stellar interactions. Therefore, for any such gaps to be consistently present in a range of globular clusters with different [Fe/H] or/and central densities, one would most likely need to invoke scenarios in which mass loss on the RGB is *not* the culprit, but rather atmospheric phenomena operating, for instance, at the transition between radiatively levitated and "normal" blue HB stars (e.g., Caloi 1999; Grundahl et al. 1999).

Indeed, even for a mass distribution along the zero-age HB (ZAHB) containing true gaps, the corresponding canonical CMD will most likely end up containing no gaps at all, as a consequence of evolution away from the ZAHB. In this sense, Caloi (1999) has pointed out that a real gap should not be seen in the CMDs of GCs at $\approx$ 10,000 K, *unless* the HB mass distribution presented a gap as large as $0.07\,M_{\odot}$. This is indeed a large gap in mass: according to the models by Catelan et al. (1998) for a metallicity $Z = 5 \times 10^{-4}$, it would be sufficient to move a ZAHB star from around the middle of the RR Lyrae instability strip to a position that is some 4000 K hotter, well into the blue HB. Clearly, it is not a trivial matter to produce a true gap along the HB, at least for typical GC metallicities. The scenario whereby increasingly hotter HB gaps are produced as a consequence of successive mass loss episodes on the RGB, possibly related to stellar encounters (or even to planet engulfment; Soker 1998), also suffers from the fact that the relative proportions of stars in between each successive (hotter) gap is not consistent with the expectations; from the lack of noteworthy differences in the radial distribution of HB stars with different colors; and from the requirement that the encounters must be fine tuned to produce mass loss amounts that are nearly the same from one star to the next (Sosin et al. 1997). Finally, and as also noted by Sosin et al., stellar encounters can certainly not be the cause of the Newell gaps among field HB stars (but see §3).

4.1. HB gaps and the production of EHB stars

The situation changes dramatically at very high metallicities though, when the range in mass between the red edge of the RR Lyrae instability strip and the extreme HB (EHB) becomes narrower, with the net effect that a small gap in mass can indeed lead to a large gap *both* in broadband colors *and* in effective temperatures (e.g., Dorman, Rood, & O'Connell 1993; D'Cruz et al. 1996; Yi, Demarque, & Kim 1997). As shown by D'Cruz et al., this result becomes especially clear when one carries out CMD simulations in which, instead of using RGB mass loss as a free parameter, one uses instead a *mass loss efficiency parameter* as the free parameter. In fact, such an approach also helps remove the "fine-tuning problem" for the production of EHB stars that has long puzzled astronomers.[2] The fact that EHB stars, but not ordinary blue HB stars, can indeed be produced at very high metallicities is dramatically demonstrated by the CMD of the old, supersolar-Z open cluster NGC 6791, which possesses a well-developed red HB co-existing alongside several stars on the *EHB* – with basically nothing in between the two groups (e.g., Kaluzny & Rucinski 1995; Landsman et al. 1998; Carraro et al. 2006).

[2] Unfortunately, it remains unclear what mass loss recipe should be used for first-ascent RGB stars (see Catelan 2007, for a critical discussion). Very recently, Origlia et al. (2007) carried out Spitzer observations of red giants in GCs, and concluded that mass loss is episodical and better described by a mass loss "law" with a very mild dependence on the evolutionary parameters of the stars (such as radius, luminosity, and gravity).

In regard to the physical origin of the EHB stars – which are the field counterparts of the blue subdwarf (sdB) stars in the field – it is important to note that, while a large fraction of field sdB stars appears to be in (close) binary systems (e.g., Maxted et al. 2001; Napiwotzki et al. 2004), the same has recently been found *not* to be the case in GCs, where EHB stars in close binary systems seem to be rare (Moni Bidin et al. 2006, 2007; Moni Bidin, Catelan, & Altmann 2008). This strongly suggests that, while binary interactions may be involved in the production of a sizeable fraction of field EHB stars, single-star mechanisms may be more efficient in the case of GCs. In fact, recent results suggest that the MS binary fractions in the outskirts of the GCs NGC 6397 and NGC 6752 are very low, thus indicating, according to the results of realistic *N*-body simulations by Hurley, Aarseth, & Shara (2007), that the *primordial* binary fraction in GCs may also have been surprisingly low (Richer et al. 2007; Catelan et al. 2008). If confirmed by more extensive observations of an enlarged sample of GCs, this may considerably limit the usage of EHB stars in globulars as indicators of what should be expected in integrated-light far-UV observations of distant field populations, including the UV upturn phenomenon in elliptical galaxies (Catelan 2007).

4.2. Plausible physical mechanisms

To be sure, certain physical mechanisms have been identified which may plausibly give rise to real HB gaps, at least in *some* observational planes. This is the case, in particular, of radiative levitation/gravitational diffusion, whose onset is quite abrupt at $T_{\rm eff} \simeq 11{,}500$ K, and which has been identified as the root cause of the so-called "Grundahl jump" that is observed in CMDs where either Strömgren's *u* or Johnson's *U* bands are used (Grundahl et al. 1999). Indeed, all stars hotter than the jump are now known to have chemical compositions that are vastly different from the original ones, whereas the cooler stars have compositions that are representative of the star's original mix (e.g., Bonifacio, Castelli, & Hack 1995; Castelli, Parthasarathy, & Hack 1997; Behr 2003a, and references therein). This abrupt discontinuity in chemical abundances can plausibly lead to observable CMD features, such as the Grundahl jump itself. Since the radiative levitation phenomenon occurs for *all* HB stars hotter than $\simeq 11{,}500$ K, one should accordingly expect that any related features in the CMD should be seen in all objects containing sufficiently hot HB stars as well.

This may be the greatest difficulty facing the association between the radiative levitation phenomenon and the "G1" gap of Ferraro et al. (1998) (see also Caloi 1999). Indeed, while the Grundahl jump *is* indeed ubiquitous (Grundahl et al. 1999), it remains unclear whether the G1 gap is present in *all* GCs with sufficiently hot HB stars. In fact, according to the calculations carried out by Grundahl et al., one expects the large abundance increases brought about by radiative levitation to have a maximum impact upon CMDs in which *u* or *U* is used. On the other hand, in the visual and in the near and far UV, the effects are expected to become much smaller.[3]

Note that the Grundahl jump is also accompanied by a discontinuity in the rotation velocities (e.g., Behr 2003a; Recio-Blanco et al. 2004): blue HB stars hotter than 11,500 K present essentially no rotation, in contrast with cooler stars which may show significant rotation velocities, up to $\sim 40\,{\rm km\,s^{-1}}$. Sweigart (2002) suggests that the low rotation velocities of stars hotter than the Grundahl jump may be due to the spin down of the surface layers by

[3] To be sure, the calculations carried out by Grundahl et al. (1999) assumed an overall enhancement of *all* metals to supersolar levels, whereas the observations indicate a wide range of enhancement levels (e.g., Bonifacio et al. 1995; Castelli et al. 1997). To the best of our knowledge, no calculations have been carried out so far in which the observed element ratios were properly taken into account – and this would be of great interest in the present context. In like vein, it remains to be seen whether the low gravities that are commonly observed over the same $T_{\rm eff}$ range as the Grundahl jump can be entirely explained in this way, or whether additional physical mechanisms, such as He mixing on the RGB, may also be required (e.g., Moehler et al. 2003).

a weak stellar wind induced by the radiative levitation of Fe (but see also Brown & Salaris 2008). As shown by Vink & Cassisi (2002), such winds are indeed predicted by theory.

At higher temperatures, another feature has recently been identified and claimed to be ubiquitous (among GCs containing sufficiently hot HB stars), namely the so-called "Momany jump," at $T_{\rm eff}$ = 21,000 ± 3000 K (Momany et al. 2004). As in the case of the Grundahl jump, this jump becomes more evident in CMDs that use the *u* or *U* bandpasses.

While its physical origin is not yet clear, Momany et al. (2004) suggested that this feature is somehow related to the *hot flashers*, which are stars that have lost so much mass during their RGB evolution that they fail to ignite He at the RGB proper, the He flash taking place after the star has "peeled off" the RGB (Castellani & Castellani 1993; D'Cruz et al. 1996; Brown et al. 2001; Cassisi et al. 2003). However, the fact that the hot flashers appear at $\simeq$ 35,000 K, which is much hotter than the Momany jump, casts some doubt on this interpretation. As in the case of the Grundahl jump, another explanation could be that abrupt chemical composition changes, again related to diffusion/levitation effects, take place at $\approx$ 21,000 K, thus giving rise to the suggested feature.

There are two types of hot flashers – *early* and *late* flashers. The former succeed in igniting He prior to the He white dwarf (WD) cooling curve, whereas the latter ignite He only after the star has started climbing down this curve. Most interestingly, late flashers, as opposed to the early flashers, are predicted to undergo extensive mixing between the He core and the envelope, thus becoming enriched in He and C. As a consequence, early flashers are predicted to arrive at the ZAHB at a position near the end of the canonical EHB, whereas the ZAHB position for the late flashers becomes over 5000 K hotter (and somewhat fainter; see, e.g., Fig. 9 in Brown et al. 2001, or Fig. 2 in Moehler et al. 2002), giving rise to the so-called "blue hook" that is observed in far-UV GC CMDs. Whether the predicted gap in ZAHB temperatures and surface chemical composition translates into a real gap being observed on the CMD again depends on the exact bandpasses used (see, e.g., Fig. 16 in Brown et al. 2001); also, a gap may be at least partly washed out by the effects of evolution away from the ZAHB. Unfortunately, there are not many GCs with sufficiently hot HB stars that the late flasher predictions can be verified on the basis of large samples: at present, the only GCs with confirmed blue hook stars are ω Cen (Whitney et al. 1998; D'Cruz et al. 2000), M54 = NGC 6715 (Rosenberg et al. 2004), NGC 2419 (Ripepi et al. 2007), NGC 2808 (Brown et al. 2001), NGC 6388, and (possibly) NGC 6441 (Busso et al. 2007). However, the available evidence seems rather encouraging, and indeed appears to favor the late flasher scenario for the production of extremely hot HB stars beyond the classical EHB limit, over such alternatives as the He polution scenario (Moehler et al. 2002, 2007; Lanz et al. 2004). Finally, RGB stars that lose even more mass than the blue hook progenitors will miss the HB phase completely, evolving directly down the WD cooling curve and never igniting He in their cores, thus becoming He WDs (e.g., Kalirai et al. 2007; Castellani et al. 2007).

5. HB multimodality

While the empirical evidence for real gaps may remain somewhat dubious, HB multimodality seems to rest on a much stronger footing. At least in a few clusters, the evidence for two or more modes on the HB has recently been traced down to multiple populations on the subgiant branch (SGB) or/and the MS.

Even then, one should still be careful to avoid overinterpreting the data for HB stars. Indeed, depending on the type of observations carried out, modes can be naturally generated *without* any physical parameter of the HB stars presenting a multimodal distribution. This is well known to happen in the case of optical CMDs; here, a continuous and uniform mass distribution can easily lead to a bimodal distribution in HB colors (see Fig. 15 in Catelan et al. 1998), simply because of the saturation of optical colors for the hot blue HB stars. Quite often, to avoid confusion, multi-band photometry, including the near- and far-UV, is needed to better track the variation in the stellar physical parameters, such as mass, effective temperature, and gravity, along the HB (e.g., Ferraro et al. 1998; Busso et al. 2007).

NGC 2808 is by far the best documented case of a GC with a multimodal HB – but it is unlikely to be the only one. Catelan et al. (1998) classify as "bimodal HBs" all those GCs which present a deficit in the RR Lyrae number counts, compared to both red and blue HB stars. NGC 2808 has long been known to have a well-populated red HB component coexisting with a blue HB, with little in between – i.e., at the RR Lyrae "gap" (Harris 1974).[4] More recent photometry has revealed that NGC 2808 actually *does* contain a significant RR Lyrae component, though with many fewer stars than either its red or blue HB counterparts (Corwin et al. 2004). In addition, deeper wide-field studies, as well as high-resolution HST photometry of the innermost cluster regions, have revealed an amazing superposition of what appear to be well-defined modes along the blue HB of the cluster (e.g., Bedin et al. 2000; Castellani et al. 2006).

Very recently, it has been shown that the NGC 2808 MS is actually comprised of three distinct components, which are more straightforwardly explained as three different populations with different helium abundances but nearly the same metallicities (D'Antona et al. 2005; Piotto et al. 2007). It is, of course, very tempting to associate these different MSs to the different HB components that are present in the cluster, and Piotto et al. point out that the different proportions of stars along the main branches of the cluster appear tantalizingly consistent with this notion.

[4] As pointed out by Catelan (2005), the term RR Lyrae "gap" is very inadequate, but is still commonly used. This is because, in order to properly place an RR Lyrae in a CMD, one needs to follow its whole pulsation cycle and thereby obtain reliable mean colors and magnitudes. Since most CMD studies lack adequate time coverage, these variable stars are often simply omitted from the published CMDs, thereby leading to an *entirely artificial* empty space, or "gap," between the red and blue HB components.

The association of abundance anomalies with HB morphology was originally advanced by Norris (1981), Norris et al. (1981), and Smith & Norris (1983) in the context of CN variations, and by Catelan & de Freitas Pacheco (1995) in the context of super oxygen-poor stars. More recent studies include, among others, those by Carretta et al. (2007) and D'Antona & Ventura (2007). The observation of abundance anomalies among *unevolved* stars in GCs (e.g., Gratton et al. 2001) has given strong support to the notion that at least some of the variations more frequently observed among RGB stars dates back from the earliest stages in the lifes of these clusters, although deep mixing effects may still play a relevant role in explaining some of the abundance patterns observed in giants (e.g., Sneden et al. 2004; D'Antona & Ventura 2007). Still, it remains unclear how high levels of He enrichment can be produced among GC stars without an accompanying change in metallicity (see, e.g., Karakas et al. 2006; Bekki et al. 2007a,b; Choi & Yi 2007). In any case, it must be noted that the origin of the hottest stars lying on the extension of the EHB – the blue hook stars (§4.2) – *cannot* be entirely explained in terms of the high He scenario, their observed properties being instead most consistent with the late-flasher scenario (Moehler et al. 2007).

It remains to be seen how many GCs will present convincing evidence for primordial abundance variations, since most globulars still appear to be well described within the framework of simple stellar populations (Piotto 2008, this volume). Indeed, only the most massive globulars have been found or suggested to contain composite populations; so far the evidence for multiple MSs or/and SGBs remains restricted to the cases of ω Cen, NGC 2808 (Piotto et al. 2007), and NGC 1851 (Milone et al. 2007) – though other massive clusters, such as NGC 6388 and NGC 6441, are also suspected of harboring heterogeneous populations, with a direct impact upon their observed HB morphologies (e.g., Busso et al. 2007; Caloi & D'Antona 2007).

It is important to note that the three GCs for which composite CMDs have been conclusively established (i.e., NGC 1851, NGC 2808, and ω Cen) all differ in important respects. More specifically, ω Cen appears to be affected by *both* metallicity *and* He abundance variations, with a large age spread also being present, whereas in NGC 2808 no spread in age or metallicity has been detected. The SGB split observed in NGC 1851 is formally consistent with two populations differing in age by $\sim$ 1 Gyr; however, according to the models by Catelan et al. (2001) and Catelan (2005) in their study of the pair NGC 288/NGC 362, such an age spread would be insufficient to explain the HB bimodality observed in the cluster. Note, in addition, that the deep photometry by Milone et al. (2007) reveals a very tight MS, indicating that there is unlikely to be a sizeable metallicity or He spread in this GC. On the other hand, Grundahl (2003) has noted that NGC 1851 differs from NGC 288 and NGC 362 in that it presents scatter in both the Strömgren c_1 and m_1 indices, and suggests that the m_1 spread in particular could be due to a spread in CN. It remains to be seen whether these CN variations would be able to explain the SGB split and bimodal HB of the cluster.

To close, we note that another HB mode may be present at the very *red* end of the HB, comprised of *blue straggler star* (BSS) *progeny*. Indeed, one should naturally expect that BSS, once they evolve away from the MS and start burning He in their core, will become red clump stars, thus tending to be brighter, redder and more luminous than regular red HB stars (see §§2.1 and 2.2 in Catelan 2005 for a recent discussion). These stars have been called "evolved BSS," or E-BSS, by Ferraro et al. (1999). Therefore, in GCs containing large numbers of BSS, a small E-BSS component is expected to be present, with of order 1 E-BSS star for every six or so BSS (Fusi Pecci et al. 1992). Indeed, such a component has been tentatively identified in several clusters (e.g., Fusi Pecci et al. 1992; Ferraro et al. 1999; Sandquist & Bolte 2004).

6. Conclusions

The empirical evidence for HB gaps has become weaker over the past several years, with several previously reported such features having become at least partly filled as more and better data have become available. It does not appear very likely at present that *all* GCs have HB gaps. Still, plausible mechanisms for the production of some HB gaps have been advanced, generally involving a sharp discontinuity in surface chemical abundances with temperature. Such a discontinuity may be brought about by radiative levitation, which leads to the "Grundahl jump" at $T_{\rm eff} \simeq 11{,}500$ K, or by a late hot flasher, which leads to a predicted gap in ZAHB temperatures beyond the end of the canonical EHB. Such phenomena may lead to significantly different CMD features depending on the bandpasses used: in some planes, "jumps" and "gaps" may become much more apparent than in others.

In contrast, the empirical evidence for multimodal HBs has become significantly stronger lately. As a matter of fact, in several cases HB multimodality has been successfully traced to multiple sequences on the SGB or/and the MS, and in some such cases He enrichment, not necessarily accompanied by an increase in metallicity, is strongly suspected to be the culprit. HB multimodality does not appear to have a single origin though, and more data and theoretical studies are required before we are in a position to claim that we fully understand the origin of multimodal HB distributions.

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