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On the gap in horizontal branches at B – V about zero

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Abstract. It is proposed that the gap observed in the horizontal branch sequence of many globular clusters at $B-V$ about zero is due to a surface phenomenon. Stars on the hotter side of the gap – $T_{\rm eff} \gtrsim 10000$ K – have an atmospheric chemical composition altered as in peculiar A and B stars. The appearance of a convective regime in the surface layers at the temperature and gravity of the gap cancel the peculiarities: it is proposed that the ensuing changes in surface physical conditions give origin to the observed gap.

Key words: Galaxy: globular clusters: general – stars: horizontal-branch – stars: chemically peculiar

1. Introduction

Non uniform star distributions are evident in many horizontal branches (see, e.g., Crocker et al. 1988). Here we examine the gap at $B-V \sim 0$ that shows up in the horizontal branch (HB) of many clusters. A detailed example is described by Walker (1994, Fig. 13) for M68: a group of eight HB stars are distinctly separated from the remainder (51) of the blue HB members, with the gap occurring at $B-V \sim 0.0$, ranging from $V = V_{\rm HB} + 0.5$ to $V_{\rm HB} + 0.7$ (see Fig. 1).

A similar gap, that is, at about the same colour and with the same magnitude width, shows up in a wide variety of HB morphologies, as it appears from the list of the clusters in which available photometry allows to recognize its presence (Table 1).

We notice some facts:

- the gap is present in clusters of very different heavy element content, from the most metal poor (NGC 5053, M68) to intermediate and metal rich (M13, NGC 1851);
- the gap is present in clusters of very different total mass and degree of central concentration, from the small and sparse NGC 5053 to the massive and post-core collapse M15;
- the gap is found also in a cluster (Terzan 8) belonging to a satellite of the Milky Way, the dwarf spheroidal galaxy in Sagittarius;
- below the gap there may be few stars or large part of the HB population.

The presence of a gap in such a variety of physical conditions, and at the same location in the CM diagram, is difficult to understand in terms of some peculiar feature in stellar structure or in the mass loss process, as it has been recognized by all researchers on the subject (see, f.e., Sosin et al. 1997, Ferraro et al. 1998)

2. Possible origins of the gap

2.1. The gap and mass loss

If mass loss during red giant evolution gives origin to the gap, the mechanism should be finely tuned with [Fe/H], since the gap is located at $B-V \sim 0$ in clusters with different metal content and the HB mass at a given colour is a function of [Fe/H].

Also the indifference of the gap to cluster central density argues against an origin from mass loss. There are by now clear indications that the environment in the cluster has a substantial influence on HB morphology. A dense environment appears to favour mass loss, at least in the sense of increasing the spread towards the largest losses (see Buonanno et al. 1985; 1997 and references therein). Therefore, if mass loss is enhanced by interactions in dense cores, it appears unlikely that a gap in mass could be mantained in the horizontal branches of post-core collapse clusters such as M15 or M30. If some physical effect, active during the red giant evolution, requires the formation of the gap at $B-V \sim 0$ in the HB population, the mass loss due to the independent mechanism of gravitational interactions should smear it out.

2.2. The gap and stellar evolution

It has been suggested (Newell 1973, Lee et al. 1988) that changes in the evolutionary pattern for stars leaving the zero age HB can give origin to the gap mentioned above. In our recent computations (Mazzitelli et al. 1995, Caloi et al. 1997) we did not find obvious pattern changes at temperatures about 10^4 K (corresponding to $B-V = 0$) for *all* chemical compositions. In any case, in all available tracks for very metal poor structures ($10^{-4} \leq Z \leq 3\ 10^{-4}$) there is no change in the pattern along which the models evolve out of the zero age HB at the indicated temperature. So at least for very metal poor clusters such an explanation is not applicable. Given the strict similarity among

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Table 1. A list of clusters which show clearly a gap in the HB star distribution at $B - V \sim 0$. The values of [Fe/H] are from Zinn 1985, except for Terzan 8 (Da Costa & Armandroff 1995); total visual magnitudes are from Djorgovski 1993; central concentrations from Trager et al. 1993.

Name	[Fe/H]	M_v	c	Ref. CMD
NGC 288	−1.40	−6.63	0.96	Buonanno et al. 1984
NGC 1851	−1.33	−8.39	2.24	Parise et al. 1994
NGC 1904	−1.68	−7.90	1.72	Kravtsov et al. 1997
NGC 2419	−2.10	−9.53	1.40	Harris et al. 1997
NGC 4590 M68	−2.09	−7.73	1.64	Walker 1994
NGC 5053	−2.58	−7.07	0.82	Sarajedini & Milone 1995
NGC 5897	−1.68	−7.27	0.79	Ferraro et al. 1992
NGC 5904 M5	−1.40	−8.82	1.87	Brocato et al. 1995
NGC 6205 M13	−1.65	−8.51	1.49	Arp & Johnson 1955; Paltrinieri et al. 1998
NGC 6341 M92	−2.24	−7.92	1.81	Sandage 1970; Buonanno et al. 1985
Terzan 8	−1.99	−5.01	0.60	Montegriffo et al. 1998
NGC 7078 M15	−2.15	−9.00	2.50	Buonanno et al. 1985
NGC 7099 M30	−2.13	−7.61	2.50	Buonanno et al. 1988 (Field 1)

gaps in clusters of widely differing metal content, we tend to exclude such an explanation also for less metal poor systems.

There is another difficulty for what concerns stellar evolution. Let us consider M68 (Walker 1994) and the tracks by Mazzitelli et al. (1995) and Caloi et al. (1997, but see also Dorman et al. 1993, Sweigart 1987, Lee & Demarque 1990) for $Z = 0.0003$. The comparison with the CM diagram of M68 in Fig. 1 (from Figs. 13 and 16 in Walker's paper) suggests star masses below the gap of about 0.645–0.65 $M_{\odot}$, while above the gap masses appear to be $\geq 0.665\ M_{\odot}$. A similar mass gap of about 0.015 $M_{\odot}$ has been estimated by Walker (1994) on the basis of Dorman (1992) tracks.

The dots on the track for 0.645 $M_{\odot}$ are placed at the position of the zero age and at intervals of 10 Myr; the track ends at an age of 67 Myr, when central helium abundance is 0.10 (by mass). In the extreme hypothesis that the clump of 7–8 stars below the gap is due to the evolution of one single mass, we would expect to find in the gap 2–3 stars. A mass spread up to 0.65 $M_{\odot}$ would be sufficient to fill completely the gap. We are dealing with the statistics of small numbers, but in *all* clusters the gap appears neatly defined (devoid of stars). In particular, this is the case of NGC 5053, in which the gap isolates a small clump of 8 stars, exactly as in M68 (Sarajedini & Milone 1995).

Clusters with a substantial population below the gap, reaching high effective temperatures (such as M15), could develop a zone of avoidance (but not as clean as the observed ones) if the mass distribution on the HB would present an interruption of about 0.07 $M_{\odot}$, in order to balance the slow "vertical" evolution mentioned above. It would be clearly an artificial solution, if not valid also for the clusters with few HB members below the gap.

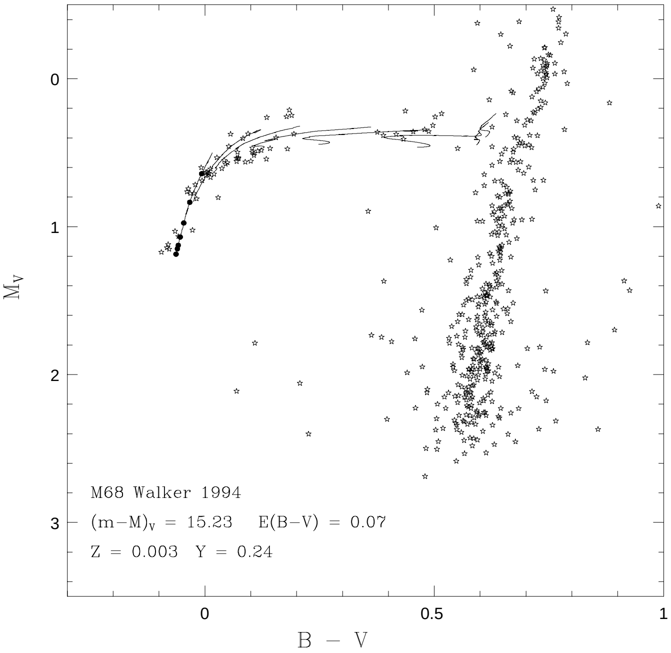

Fig. 1. The HB of M68 from Walker 1994 with superimposed tracks from Mazzitelli et al. 1995; tracks for the lowest masses (0.645 and 0.665 $M_{\odot}$) shown in the figure have been computed for the occasion. Dots indicate steps of 10^7 yr.

3. The atmospheric connection

If dynamical or structural causes for the avoidance of the HB region around *(B – V)* ~ 0 are excluded, we are left with *atmospheric* phenomena, characteristic of conditions prevailing at these temperatures. This means that we look for disturbances in the surface layers which alter colours and magnitude in stars across the gap: the obvious candidate is given by the chemical peculiarity expected (and observed in some case) in stars on the hot side of the gap, as we shall discuss in the following.

3.1. Some properties of CP stars

To give an idea of the situation we expect, we recall briefly some properties of Population I chemically peculiar (CP) stars.

Chemically peculiar stars are mostly found among main sequence members of spectral type A and late B. It was early recognized that the changes in atmospheric composition induced by element diffusion may affect stellar photometric properties (Deutsch 1947). The main observed effects are an ultraviolet flux deficiency (Leckrone 1973), because of the increased opacity in the ultraviolet spectral region, and the formation of broad, continuous absorption features at λ 4200, 5300 and 6300 A (Maitzen & Moffat 1972, Adelman 1975).

As a consequence, the overall flux distribution of a chemically peculiar star may depart from the one of a normal main sequence star with the same total flux. Many photometric indices are altered, due to the strong blanketing originating from the ultraviolet flux deficiency mentioned above and to the broad depressions in the continuum. In particular, the broad depression at 5200 A is reported to alter the flux in the *V* and *y* filters (Gerbaldi et al. 1974, Hauck & North 1982, Stepien & Dominiczak 1989); the effect on the continuum of peculiar stars is shown, f.e., in Adelman (1975).

For all these reasons it may be necessary to distinguish between effective temperature, which is a measure of the total luminosity of the stars, and the temperature of the line forming region, the latter being the temperature that must be used in atmospheric modeling and abundance analysis (Wolff 1983).

It has been known for a long time that Population II stars may present the same peculiarities in chemical composition found in Population I Bp and Ap stars (Sargent & Searle 1967, Baschek & Sargent 1976 and references therein). The Pop. II stars involved were field blue horizontal branch objects; a general helium and carbon deficiency is coupled to an overabundance of a variety of heavy elements such as Si, P, Fe, Mn etc.

As expected, also hot HB stars have been observed to exhibit similar peculiarities. Helium underabundance has been found in HB stars of the cluster NGC 6752 (Heber et al. 1986); for one of these stars ($T_{\rm eff}$ = 16000 K) the underabundance has been confirmed by Glaspey et al. (1989), who found also a strong overabundance of Fe by a factor of at least 50 compared to the cluster metallicity. No anomalies, or at least not as strong, were observed in a star in the same cluster with $T_{\rm eff}$ = 10000 K. Also Lambert et al. (1992) found a composition consistent with the cluster metallicity in a star with $T_{\rm eff}$ = 9000 in NGC 6397.

At variance with the situation in Pop. I, no substantial UV deficiency has been observed in hot HB stars. For the chemically peculiar halo HB star Feige 86 (Sargent & Searle 1967), the $T_{\rm eff}$ estimated from the visual spectrum (17500 K; Baschek & Sargent 1976) turns out very close to the one determined from the energy distribution in the wavelength interval 1200–3000 A by the *International Ultraviolet Explorer* (18000 K; Hack 1979, 1980).

The available *IUE* spectra for globular cluster blue HB members (Heber et al. 1986; Cacciari et al. 1995; de Boer et al. 1995) show minor deviations (if any) from the predictions of Kurucz' models (1979, 1993), for temperatures determined from (or consistent with) the continuum level in the visual range and Balmer line profiles. Substantial deviations in the UV like those observed in Pop. I stars (Leckrone 1973, Stepien & Dominiczak 1989) are not encountered, probably because the metal enrichment appears to barely reach the solar abundance, while much higher abundances are generally found in Pop. I peculiar stars.

Also the continuum depressions are not evident. So the main discrepancies found in CP Pop. I stars seem to be absent, but we have to stress that the level of precision reached in the analysis of main sequence CP Pop. I atmospheres has not yet been attained in the case of hot HB objects. In any case, there are some hints of discrepancy among temperature estimates from photometric indices, UV continuum, visual continuum and Balmer lines. They will be discussed later, after a brief description of current views on the causes of chemical peculiarities in HB stars.

3.2. Theoretical interpretation of chemical peculiarities in HB stars

Helium underabundance is generally understood in terms of helium sedimentation (Greenstein et al. 1967), while a radiative acceleration larger than gravity accounts for – at least in principle – the overabundance of the heavy elements (Michaud et al. 1983). The situation expected in HB stars is illustrated by Michaud et al. (1983) for Z = 0.0001 and Y = 0.20. For the 0.74 $M_\odot$ model ($T_{\rm eff}$ = 6300 K, log g = 2.9) the effects of helium diffusion show up on a time scale comparable to the HB lifetime (about 10^8 yr), while the surface helium abundance in the 0.66 $M_\odot$ model ($T_{\rm eff}$ = 8400 K, log g = 3.4) declines substantially in about 10^7 yr, even in presence of some turbulence. For lower masses, the efficiency of sedimentation increases.

As for the heavy elements, the radiative acceleration on them is found to be much larger than gravity, mainly because of the underabundance with respect to the sun. This fact desaturates the lines and leads to large radiative accelerations: large overabundances are therefore possible (a factor 10^4) (Michaud et al. 1983). Detailed estimates for the various elements as function of stellar mass and surface temperature are not yet available. Beside the theoretical difficulties, one meets with the uncertainties on the depth of the hydrogen and helium convection zones, the amount of turbulence, the rotational velocity, the efficiency of mass loss etc. According to Vauclair et al. (1974) diffusion begins to be effective at a temperature $\sim$ 10000 K. Michaud et al. (1983) consider most unlikely the formation of large anomalies for $T_{\rm eff} \lesssim$ 6000 K; more stringent constraints are prevented by the lack of knowledge quoted above on the status of motion of the outer stellar layers (see also Charbonneau & Michaud 1988).

Some estimates exist for the effects of meridional circulation on diffusion efficiency. Michaud (1982) finds a strong decrease with decreasing gravity of the maximum rotational velocity still allowing helium sedimentation (90 $\rm km\,s^{-1}$ if log g = 4.4, 4 $\rm km\,s^{-1}$ if log g = 3.5), in the case of main sequence stars. Similar calculations are not available for HB stars, but the qualitative behaviour should be the same. Glaspey et al. (1989) find, for the hotter star in NGC 6752 ($T_{\rm eff}$ = 16000 K), v sin i $<$ 15 $\rm km\,s^{-1}$, and for the cooler one ($T_{\rm eff}$ = 10000 K), 30 (± 10) $\rm km\,s^{-1}$: actually, as mentioned above, Fe overabundance is observed only in the hotter object.

4. Above and below the gap

In the accurate photometry by Walker (1994) for M68, the gap appears located at $B - V \simeq -0.05$ (E_{B-V} = 0.07 mag), corresponding to $T_{\rm eff} \simeq 11000$ K (Kurucz transformations 1993 for [Fe/H] = -2). Moehler et al. (1994) find indication for a low temperature gap in the HB of NGC 6752 at Log $T_{\rm eff} \sim 4.08$ (12000 K). Of the two stars studied by Glaspey et al., the one without substantial composition anomalies lies above the gap at $T_{\rm eff}$ = 10000 K, while the one with a strong Fe overabundace lies below at $T_{\rm eff}$ = 16000 K. Other clusters confirm the position of the gap: Crocker et al. (1988) estimate $T_{\rm eff} \approx$ 11–12000 K for NGC 288, while in M15 the gap is given at $T_{\rm eff} \sim 10000$ K (Moehler et al. 1994, 1995).

So there are indications that: the gap is located at a temperature for which diffusion in HB stars begins to be effective, and stars at $T_{\rm eff}$'s lower than this critical one do not develop abundance anomalies in the atmosphere, while stars with higher $T_{\rm eff}$'s do. The gap itself would take origin by the disappearance (through mixing) of surface composition anomalies. The mixing would be induced by changes taking place in stellar structure and atmosphere when, during evolution, the effective temperature becomes lower than about 10–12000 K. Such changes can include an increasing size of the convective zone(s), an increase in turbulence and mass loss, a decrease in surface gravity, etc.

We suggest that CP stars exhibit sufficient “irregular” features in their photometric and spectral properties that the return to normality may imply observable discontinuities not only, as obvious, in their spectral characteristics, but also in the photometric ones. It is possible that some such discrepancies in the atmospheric properties of HB objects located below the gap have already been observed.

Many authors have found that blue HB stars tend to lie above the zero age HB locus, in the plane $T_{\rm eff}$–log g. The shift appears on the average more pronounced for temperatures greater than $\sim$ 13000 K; for temperatures about 20000 K (the subdwarf B region) the discrepancy disappears (Crocker et al. 1988, Rood & Crocker 1988, de Boer at al. 1995, Moehler et al. 1995).

In their analysis of blue HB stars in M15, Moehler et al. (1995) derive temperatures from the Balmer lines which are systematically hotter than those derived from the Balmer continuum, with differences up to 4–5000 K (in the range 16–20000 K, Balmer line scale). Regarding M3, Cacciari et al. (1995) compare their values of $T_{\rm eff}$ derived from the UV continuum (*IUE* observations) with estimates by Crocker et al. (1988) using the continuum and the Balmer lines, and find that these latter ones are on the average hotter of about 1400 K (in the range 10–15000 K). From Crocker et al.'s data it is not possible to decide whether their higher temperatures are to be attributed to the continuum or to the lines.

A way to understand these deviations from the expected behaviour may lie in the results by Leone & Manfre' (1997). They have determined the temperature and gravity of three Pop. I chemically peculiar stars of about 14000 K, by matching the H_β line profile. They find that, when helium and metal contents in the ATLAS9 atmospheric model matching the profile do not correspond to the composition peculiarities observed in the star, the estimates for temperature and gravity may turn out substantially different from the estimates with model atmospheres adopting the correct (observed) composition.

As a general feature, helium deficiency tends to compensate for metal over–abundance effects, so that various combinations of under– and over–estimates are possible. In particular, when the atmosphere shows a strong metal enrichment and a slight helium depletion, both temperature and gravity are underestimated. For star HD 175362, with 10 times the solar metallicity and $n_{\rm He}/n_{\rm tot}$ = 0.05, the temperature obtained assuming in the atmospheric model the observed composition is 14600 K (instead of 13600 K, solar composition). As for the gravity, the estimate of log g moves from 3.45 (solar composition) to 3.70 (observed composition).

The estimates by Heber et al. (1986) and Caloi et al. (1986) show that, in the (exclusively) blue HB of NGC 6752, helium abundance decreases with increasing gravity ($y = n_{\rm He}/(n_{\rm H} + n_{\rm He})$= 0.03 for log g = 4, $y \approx 0.0003$ for log $g \geq 5$). For star 1083 in this cluster ($T_{\rm eff}$ = 16000 K, log g = 4), Heber et al. give y = 0.03, and Glaspey et al. (1989) estimate a Fe enhancement from 30 to 150 times the original cluster abundance ([Fe/H] = -1.5): so we are in presence of a strong metal enrichment and a mild helium deficiency, as in HD 175362.

We can assume that an atmospheric analysis performed without taking into account such chemical peculiarities is likely to give results deviating from the behaviour $T_{\rm eff}$ *vs* log g expected in blue HB stars, in the sense remarked by the authors quoted above, that is, gravities too low at a given temperature. The normal behaviour of B subdwarfs with their large helium depletion is also understood in this context, given the compensating effects between metal enhancement (supposedly present) and helium deficiency.

5. Conclusion

It is proposed that the origin of the gap observed at $B - V$ about 0 in the horizontal branch sequence of many globular clusters is due to an *atmospheric* phenomenon. The stars below the gap have their flux distribution altered by the chemical peculiarities induced by settling and radiation pressure. The disappearance of these peculiarities, due to the mixing of the atmospheric layers at a surface temperature of about 10000 K, gives origin to the avoidance region in question.

Admittedly, the reasons in favour of such an explanation for the gap at $B - V \simeq 0$ are at present rather speculative. The hypothesis can easily be verified with the acquisition of high dispersion spectra of objects just below and above the gap.

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