

Spectroscopic analyses of the “blue hook” stars in ω Centauri: A test of the late hot flasher scenario

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Abstract. ω Cen contains the largest population of very hot horizontal branch (HB) stars known in a globular cluster. Recent UV observations (Whitney et al. 1998; D’Cruz et al. 2000) show a significant population of hot stars below the zero-age horizontal branch (“blue hook” stars), which cannot be explained by canonical stellar evolution. Stars which suffer unusually large mass loss on the red giant branch and thus experience the helium core flash while descending the white dwarf cooling curve could populate this region. Theory predicts that these “late hot flashers” should show higher temperatures than the hottest canonical HB stars and should have helium- and carbon-rich atmospheres. We obtained and analysed medium resolution spectra of a sample of blue hook stars to derive their atmospheric parameters. The blue hook stars are indeed both hotter ($T_{\text{eff}} \geq 35\,000$ K) and more helium-rich than classical extreme HB stars. In addition we find indications for a large enhancement of the carbon abundance relative to the cluster abundance.

Key words. stars: horizontal-branch – stars: evolution – Galaxy: globular clusters: individual: NGC 5139

1. Introduction

Horizontal-branch (HB) stars consist of a helium-burning core of about $0.5 M_{\odot}$ surrounded by a hydrogen-burning shell and a hydrogen-rich envelope of varying mass. The temperature of an HB star (at a given metallicity) is determined by the mass of its hydrogen envelope, with the envelopes of the cooler HB stars being more massive. The increase in the bolometric correction with increasing temperature turns the blue HB into a vertical blue tail in optical colour-magnitude diagrams (CMDs, cf. Fig. 1) with the faintest blue tail stars being the hottest and least massive. The hottest HB stars (so-called extreme HB or EHB stars) with $T_{\text{eff}} > 20\,000$ K have so little envelope mass that they are unable to sustain hydrogen-shell burning. Nearly all of their surface luminosity comes from helium burning in the core. Such EHB stars can be identified with the subdwarf B (sdB) stars in the field of the Milky Way and are believed to be mainly responsible for the UV excess observed in the spectra of elliptical galaxies. The globular cluster ω Cen possesses an

especially long blue tail containing the largest known population of EHB stars in a globular cluster.

Observations of ω Cen in the far-UV (Whitney et al. 1998; D’Cruz et al. 2000) revealed a puzzling feature: the very hot end of the HB shows a surprisingly large spread in UV brightness, including a substantial population of subluminoous stars lying up to 0.7 below the zero-age HB (ZAHB). Such subluminoous EHB stars are so far known to exist only in one other globular cluster (NGC 2808; Brown et al. 2001; Sweigart et al. 2002). While stars brighter than the ZAHB can be produced by evolution away from the ZAHB, the stars fainter than the ZAHB cannot be explained by canonical HB evolution. Within the framework of canonical HB theory there is no way to populate this region of the UV CMD without requiring an implausibly large decrease in the helium-core mass. The subluminoous EHB stars appear to form a hook-like feature in the UV CMD and are therefore called “blue hook” stars. In optical CMDs these stars show up at the very faint end of the blue tail (cf. Fig. 1), in agreement with the high temperatures suggested by their UV photometry.

The blue hook stars in ω Cen populate a range in absolute visual magnitude that extends beyond the faint limit of the long blue tail in NGC 6752, which has been studied extensively by

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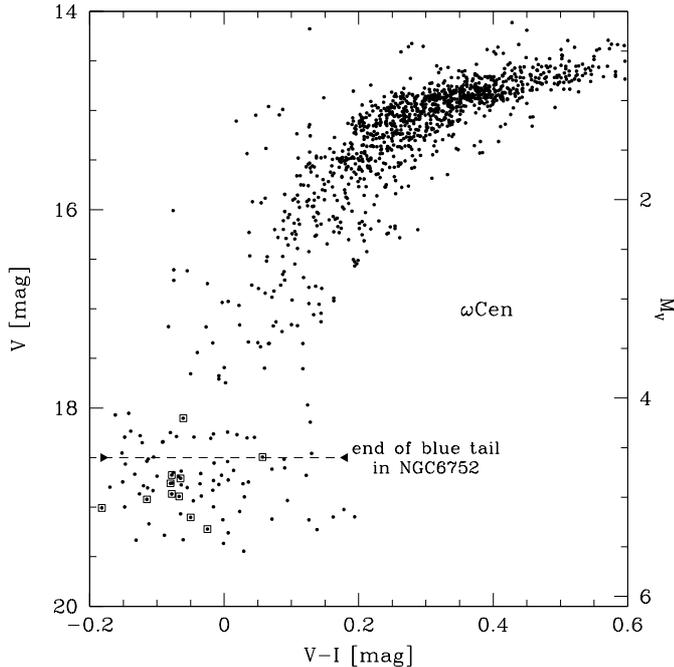


Fig. 1. Colour-magnitude diagram of the blue tail of ω Cen (Kaluzny et al. 1997) with the spectroscopic targets marked. To establish the absolute magnitude scale on the right side apparent distance moduli $(m - M)_V$ of 13^m9 and 13^m3 were used for ω Cen and NGC 6752, respectively.

Moehler et al. (2000). That in itself would not be a problem, but the spectroscopic analyses of Moehler et al. (2000) show that the blue tail stars in NGC 6752 already populate the EHB to the hot end predicted by canonical HB models. Thus canonical theory fails to explain both the faint UV luminosities and expected high temperatures of the blue hook stars. One might suspect that hotter EHB stars could be produced by simply reducing the envelope mass even further. However, Brown et al. (2001) have demonstrated that there is a lower limit to the envelope mass of canonical EHB stars. Increasing the mass loss along the red-giant branch (RGB) will not reduce the envelope mass below this limit but instead will cause a star to die as a helium white dwarf without ever igniting helium in its core. Thus the blue hook stars may represent a new evolutionary channel for populating the very hot end of the HB.

One possibility is that the blue hook stars have undergone a delayed helium-core flash. Castellani & Castellani (1993) were the first to suggest that – for very high mass loss on the RGB – the helium flash can occur at high effective temperatures after a star has left the RGB (the so-called “hot flashers”). Indeed, D’Cruz et al. (1996, 2000) proposed that the blue hook stars could be the progeny of such hot flashers, but unfortunately the D’Cruz et al. models were, at most, only $\approx 0^m1$ fainter than the canonical ZAHB, much less than required by the observations. More recently, Brown et al. (2001) have explored the evolution of the hot flashers through the helium flash to the EHB in more detail, especially in regard to the timing of the flash. Their models show that under some circumstances the helium flash will induce substantial mixing between the hydrogen envelope and helium core, leading to helium-rich EHB stars that

are much hotter than canonical ones. Brown et al. (2001) suggest that this “flash mixing” may be the key for understanding the evolutionary status of the blue hook stars. Such mixing may also be responsible for producing the helium-rich, high gravity field sdO stars (Lemke et al. 1997), whose origin is otherwise obscure.

The purpose of this paper is to present a spectroscopic analysis of a sample of blue hook stars in ω Cen in order to test the predictions of the flash-mixing scenario. Following a brief description of this scenario in Sect. 2, we discuss our observational data and then derive the parameters of the blue hook stars (temperatures, gravities and helium abundances) in Sects. 3 and 4, respectively. In Sect. 5 we compare our results with the predictions of the flash-mixing scenario.

2. Flash-mixing scenario

In discussing the flash-mixing scenario it is essential to distinguish between “early” and “late” hot flashers, since their evolution through the helium flash differs in fundamental respects. The early hot flashers are stars which ignite helium at some point between the tip of the RGB and the top of the helium white dwarf cooling curve, i.e., before the “knee” visible in Fig. 2, and therefore at a time when the hydrogen-burning shell is a strong energy source in the star (see long-dashed line in Fig. 2). As shown by Iben (1976), a strong hydrogen-burning shell poses a formidable entropy barrier that effectively prevents the convection zone produced by the helium flash from penetrating into the hydrogen envelope. Thus an early hot flasher will settle onto the EHB without any mixing between its helium core and hydrogen envelope and consequently without any change in its envelope mass or composition. In other words such a star will follow a canonical (i.e., unmixed) evolutionary path to the EHB. The models of Brown et al. (2001), which followed the evolution of the early hot flashers through the helium flash, showed that these stars reach a maximum temperature of $\approx 31\,500$ K on the EHB. A similar maximum temperature is evident in the models of D’Cruz et al. (1996, their Fig. 2), who assumed that the helium flash had no effect on the envelopes of the EHB stars. Since the core masses of the early hot flashers are at most only $\approx 0.001 M_\odot$ smaller than the core masses of the EHB stars which ignite helium on the RGB, their luminosities will be nearly indistinguishable from the luminosities of the canonical EHB stars. While such early hot flashers would populate the clump seen in the UV CMD of ω Cen at $m_{160} - V < -3^m0$ and $14^m8 < m_{160} < 15^m3$ (D’Cruz et al. 2000), they are too bright to explain the blue hook stars.

The evolution of a hot flasher is dramatically different if the helium flash is delayed until the star is descending the white dwarf cooling curve (late hot flasher; short-dashed line in Fig. 2). The hydrogen-burning shell in a late hot flasher is substantially weaker than in an early hot flasher, and consequently it presents a much lower entropy barrier between the core and the envelope. As a result, the flash convection is then able to penetrate through the hydrogen shell into the envelope, thereby mixing hydrogen from the envelope into the core where it is rapidly burned (Sweigart 1997). At the same time helium and carbon from the core are transported outward into the

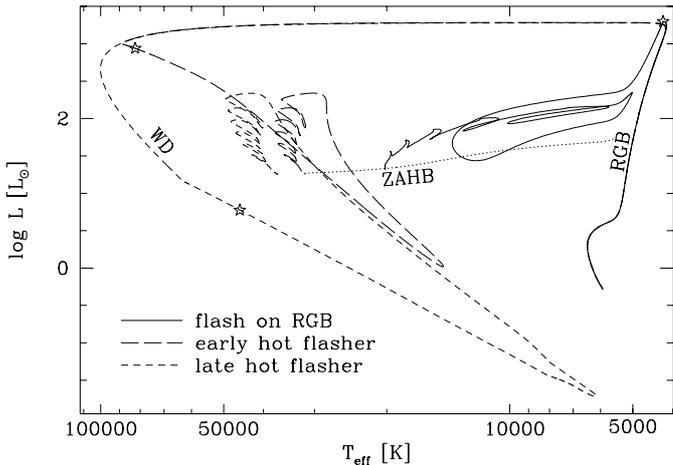


Fig. 2. Evolutionary tracks through the helium flash for a star which ignites helium on the RGB (solid line), an early hot flasher (long-dashed line), and a late hot flasher (short-dashed line). The peak of the helium flash along each track is indicated by an asterisk. The dotted line marks the canonical zero-age HB (ZAHB). The early hot flasher in this figure produces an EHB star near the hot end of the canonical HB. Note the temperature gap between this early hot flasher and the late hot flasher. All tracks are taken from Sweigart (1997).

envelope. This flash mixing is similar to the mixing that occurs during a very late helium-shell flash according to the “born-again” scenario for producing H-deficient post-asymptotic giant branch (post-AGB) stars (e.g., Iben et al. 1983; Iben 1984, 1995; Renzini 1990; Herwig 2001). Similar mixing has also been found during the helium flash in Population III stars, where the flash occurs at a much lower luminosity than in globular cluster stars (Hollowell et al. 1990; Fujimoto et al. 1990; 2000; Schlattl et al. 2001).

The calculations of Brown et al. (2001) for the late hot flashers were stopped at the onset of flash mixing due to the numerical difficulty of following the time-dependent convective mixing of the envelope hydrogen and the simultaneous nucleosynthesis within the flash convection zone. Based on the earlier models of Sweigart (1997), Brown et al. (2001) predicted that the flash convection would capture essentially all of the hydrogen envelope, thus resulting in a final envelope composition that is highly enriched in helium and triple-alpha carbon. This prediction has recently been confirmed by the detailed calculations of Schlattl & Weiss (2002, priv. comm.), who evolved two late hot flashers through the helium flash to the EHB using a diffusion algorithm for coupling the nucleosynthesis to the convective mixing. Flash mixing in these late hot flashers reduced the envelope hydrogen abundance X to $\approx 10^{-4}$ while increasing the envelope carbon abundance to ≈ 0.03 by mass. Thus only a small residual amount of the envelope hydrogen survives the flash-mixing phase.

Flash mixing introduces a dichotomy in the properties of the EHB stars that can be observationally tested. The models of Brown et al. (2001) show that the late hot flashers will lie at effective temperatures of about 37 000 K on the EHB, considerably hotter than the early hot flashers. Moreover, the transition between the early and late hot flashers is exceedingly sharp, corresponding to a difference in mass loss along

the RGB of only $10^{-4} M_{\odot}$. Thus one would expect the large temperature difference between the early and late hot flashers to produce a gap in the observed stellar distribution towards the hot end of the blue tail, as is, in fact, seen in optical CMDs of NGC 2808 (Walker 1999; Bedin et al. 2000). We also note that the change in the surface composition of the late hot flashers from hydrogen-rich to helium/carbon-rich reduces the atmospheric opacity below 912 \AA so that more of the flux is radiated in the far-UV and less at longer wavelengths. This effect together with the larger bolometric corrections of the late hot flashers resulting from their higher effective temperatures lowers their UV luminosity by ≈ 0.7 , just as observed in the blue hook stars (Brown et al. 2001). This further strengthens the argument that the blue hook stars are indeed the progeny of the late hot flashers.

In the next section we present our observational data for testing the above predictions of the flash-mixing scenario by determining the temperatures and surface compositions of the blue hook stars.

3. Observations and data reduction

Due to the predicted change in surface composition the obvious way to verify the existence of late hot flashers is by spectroscopic observations of the blue hook stars in ω Cen. We obtained medium-resolution spectra ($R \approx 700$) of 12 blue hook candidates with $18.5 < V < 19.2$ at the NTT with EMMI on February 22–25, 2001. The candidate blue hook stars in the WFPC2 photometry of D’Cruz et al. (2000) were generally too crowded for ground-based spectroscopy, although we were able to observe one star on the WF3 chip of the least-crowded pointing (WF3-1). Our remaining 11 targets come from either fields BC or C of Kaluzny et al. (1996) or field D of Kaluzny et al. (1997). For all the Kaluzny stars we derived 1520 \AA photometry from an image of ω Cen obtained with the Ultraviolet Imaging Telescope (UIT) in 1995. This photometry is slightly deeper than that reported at 1620 \AA by Whitney et al. (1998) from an earlier UIT flight. When selecting the targets we concentrated on the stars at the very hot end of the blue tail (cf. Fig. 1 and Table 1). In order to observe as many stars as possible we oriented the slit to cover two candidate stars at once if possible. This of course did not allow to reduce the light loss due to atmospheric dispersion by observing along the parallactic angle and also required observations in fairly crowded regions.

We used grating #4 (72 \AA mm^{-1}) with CCD #31 (1024×1024 pixels of 24 \mu m^2 size; $2.84 \text{ e}^-/\text{ADU}$, read-out-noise 7.3 e^-) and a slit width of $1''.0$, yielding a spectral resolution of about 6.5 \AA as determined from the $FWHM$ of the wavelength calibration lines. We observed each night ten bias frames and ten dome flat fields and for the whole run two sky flat fields to ensure a good correction of the illumination profile of the slit. At the beginning of each night we observed HeAr spectra for wavelength calibration. Due to the long integration times of the Ar lamp we observed only He spectra before and after each science exposure during the night, from which we derived the zero-points for the wavelength calibration, while the dispersion relation was derived from the HeAr frames. We observed dark

Table 1. Positions, photometric information, and atmospheric parameters of target stars.

Star	α_{2000}	δ_{2000}	V	$V - I$	m_{1520}	T_{eff} [K]	$\log g$ [cm s^{-2}]	$\log \frac{n_{\text{He}}}{n_{\text{H}}}$
WF3-1	13 ^h 26 ^m 32 ^s .5	-47°24′17″.7	18 ^m .6			35 100 ± 1600	5.80 ± 0.28	-2.18 ± 0.59
BC 6022	13 ^h 26 ^m 24 ^s .95	-47°33′23″.2	18 ^m .494	+0 ^m .057	15 ^m .50	45 600 ± 1300	6.10 ± 0.14	-1.78 ± 0.16
BC 8117	13 ^h 26 ^m 33 ^s .23	-47°35′12″.3	18 ^m .709	-0 ^m .065	14 ^m .81	29 800 ± 1000	5.48 ± 0.14	-2.30 ± 0.23
BC 21840	13 ^h 27 ^m 25 ^s .95	-47°32′19″.6	18 ^m .103	-0 ^m .061	15 ^m .19	35 700 ± 700	5.55 ± 0.14	-0.80 ± 0.14
C521	13 ^h 26 ^m 08 ^s .82	-47°37′12″.3	18 ^m .676	-0 ^m .078	15 ^m .29	34 700 ± 500	5.90 ± 0.12	-0.90 ± 0.09
D4985	13 ^h 25 ^m 14 ^s .72	-47°32′36″.0	18 ^m .867	-0 ^m .078	15 ^m .14	38 400 ± 800	6.08 ± 0.16	-0.87 ± 0.16
D10123	13 ^h 25 ^m 34 ^s .25	-47°29′50″.0	18 ^m .921	-0 ^m .115	15 ^m .21	35 000 ± 500	5.82 ± 0.12	-0.87 ± 0.09
D10763	13 ^h 25 ^m 35 ^s .57	-47°27′45″.1	19 ^m .103	-0 ^m .050	15 ^m .46	35 200 ± 1500	4.35 ± 0.19	+0.94 ± 0.14
D12564	13 ^h 25 ^m 41 ^s .34	-47°29′06″.0	19 ^m .007	-0 ^m .182	15 ^m .13	36 900 ± 1000	5.60 ± 0.14	-0.37 ± 0.09
D14695	13 ^h 25 ^m 46 ^s .54	-47°26′51″.7	19 ^m .220	-0 ^m .025	15 ^m .59	41 300 ± 700	6.11 ± 0.21	-0.22 ± 0.12
D15116	13 ^h 25 ^m 50 ^s .19	-47°32′05″.9	18 ^m .760	-0 ^m .080	14 ^m .87	41 500 ± 1100	6.11 ± 0.14	-0.21 ± 0.11
D16003	13 ^h 25 ^m 53 ^s .96	-47°35′21″.3	18 ^m .891	-0 ^m .067	15 ^m .49	36 300 ± 600	5.91 ± 0.12	-1.03 ± 0.10

frames of 3600 and 1800 s duration to measure the dark current of the CCD. As flux standard star we used Hiltner 600.

The flat fields showed slight ($\leq \pm 2\%$) variations on short timescales (\sim minutes), while the bias frames showed no variations. We therefore averaged the dome flat fields and the bias frames for all nights. The mean sky flat field and the mean dome flat field were averaged along the dispersion axis to construct their respective spatial illumination profiles. The mean dome flat field was then corrected by the ratio of the illumination profiles. By averaging the dome flat field along its spatial axis we determined the spectral energy distribution of the flat field lamp and corrected it by dividing the mean flat field through the heavily smoothed energy distribution.

For the wavelength calibration we fitted 2nd-order polynomials to the dispersion relations of the HeAr spectra (using 17 unblended lines) which resulted in mean residuals of $\leq 0.4 \text{ \AA}$. We rebinned the frames two-dimensionally to constant wavelength steps. The two-dimensional sky subtraction was performed as described in Moehler et al. (2000) with the spatial profile of the sky background described by a constant. The sky-subtracted spectra were extracted using Horne’s (1986) algorithm as implemented in MIDAS (Munich Image Data Analysis System). Finally the spectra were corrected for atmospheric extinction using the extinction coefficients for La Silla (Tüg 1977) as implemented in MIDAS. The flux data for Hiltner 600 were taken from Hamuy et al. (1992) and the response curves were fitted by splines. The flux-calibration is helpful for the later normalization of the spectra as it takes out all large-scale sensitivity variations of the instrumental setup. Atmospheric dispersion will cause light loss especially at blue end of the spectral range so that the flux distribution of the calibrated spectra cannot be used to infer temperatures (e.g. from the Balmer jump). We determined radial velocity shifts from the positions of the Balmer and He I lines. The Doppler-corrected spectra were then co-added and normalized by eye and are plotted in Fig. 3.

4. Analysis

In contrast to the somewhat brighter (in absolute visual magnitude) blue tail stars analysed in NGC 6752, which are helium deficient and show weak to no helium lines

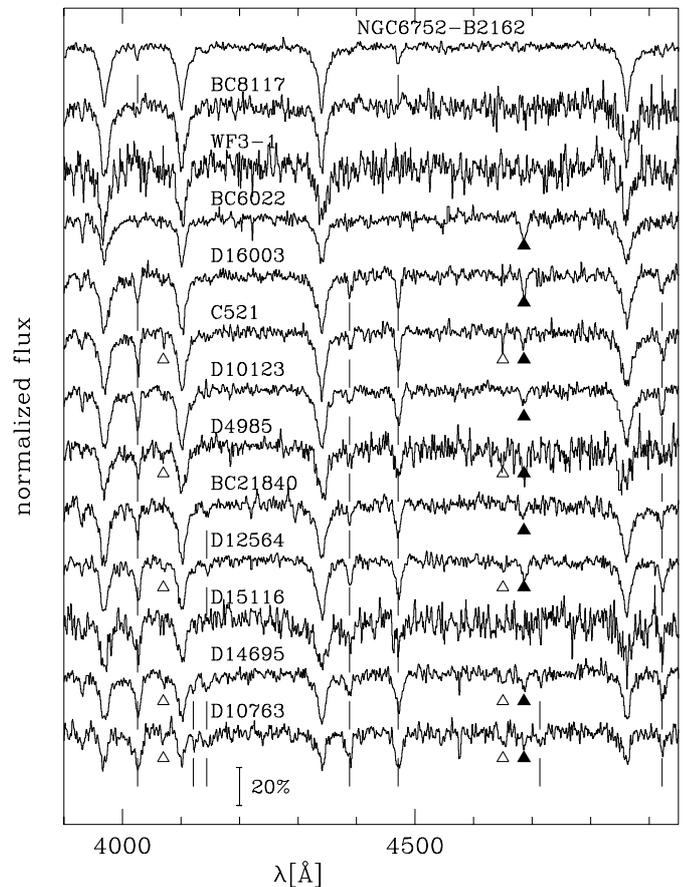


Fig. 3. Spectra of blue hook stars in ω Cen sorted according to their helium abundance. For comparison the spectrum of a star at the faint end of the blue tail in NGC 6752 from Moehler et al. (2000) is shown. The lines mark the position of the He I lines, the filled triangles mark the He II line at 4686 \AA , the open triangles mark the C III lines at 4070 \AA and the C III/N III lines at 4650 \AA .

(cf. Moehler et al. 2000 and uppermost spectrum in Fig. 3), most of the blue hook stars in ω Cen show rather strong He I lines, and some of them even show C III/N III and He II absorption (see Fig. 3).

Fits to the spectra with non-LTE model atmospheres allow to derive effective temperatures, surface gravities, and helium

abundances. The helium-rich NLTE model atmospheres were calculated with a modified version of the accelerated lambda iteration code of Werner & Dreizler (1999). The model atoms for hydrogen and helium as well as the handling of the line broadening for the spectrum synthesis are similar to those of Werner (1996). The calculation of the helium-poor NLTE model atmospheres is described in Napiwotzki (1997). To establish the best fit we used the routines developed by Bergeron et al. (1992) and Saffer et al. (1994), as modified by Napiwotzki et al. (1999), which employ a χ^2 test. The σ necessary for the calculation of χ^2 is estimated from the noise in the continuum regions of the spectra. The fit program normalizes model spectra and observed spectra using the same points for the continuum definition. The results obtained from fitting the Balmer lines H_β to H_{10} (excluding H_ϵ to avoid the Ca II H line), the He I lines $\lambda\lambda$ 4026 Å, 4388 Å, 4471 Å, 4921 Å and the He II lines $\lambda\lambda$ 4542 Å, 4686 Å are given in Table 1 and plotted in Fig. 4.

Nine of the twelve stars show at least solar helium abundance¹ (as opposed to the hottest EHB stars in NGC 6752, which show helium abundances of ≤ 0.1 solar, Moehler et al. 2000) and four have a helium abundance by particle number of ≥ 0.4 (corresponding to $Y \geq 0.7$). The only other globular cluster blue tail star which has been found to show a super-solar helium abundance is M 15 F2-2 (Moehler et al. 1997), which is also quite hot ($T_{\text{eff}} \approx 36\,000$ K).

Synthetic NLTE spectra suggest that a somewhat super-solar carbon abundance of $[C/H] \approx +0.5 \pm 0.5$ is required to explain the CIII features, although a quantitative analysis will require higher quality spectra. As noted in Sect. 2, an enhanced carbon abundance in the blue hook stars is predicted by the flash-mixing scenario.

5. Discussion

Our analysis of the blue hook stars in ω Cen shows that these stars do indeed reach effective temperatures of more than 35 000 K (cf. Fig. 4 and Table 1), well beyond the hot end of the canonical EHB. In addition, most of them show at least solar helium abundances with the helium abundance increasing with effective temperature (cf. Fig. 4), in contrast to canonical EHB stars such as those studied in NGC 6752 by Moehler et al. (2000). We now discuss both of these results in more detail.

The coolest star in our sample (BC8117) at $T_{\text{eff}} \approx 30\,000$ K lies near the hot end of the canonical EHB and shows the same low helium abundance as the EHB stars in NGC 6752 (see Fig. 4). Most likely, BC 8117 is the descendant of an early hot flasher. All of the other stars in our sample have temperatures $\gtrsim 35\,000$ K and, except for the low gravity star D10763, lie in the general vicinity of the track for a late hot flasher in Fig. 4. Although limited, our data suggest that the blue hook stars may be separated from the canonical EHB stars by a temperature gap from $\approx 31\,000$ K to $\approx 35\,000$ K. As discussed in Sect. 2, such a temperature gap is predicted by the flash-mixing scenario.

The HB track for the early hot flasher in Fig. 4 passes through the temperature gap, thus raising the possibility that

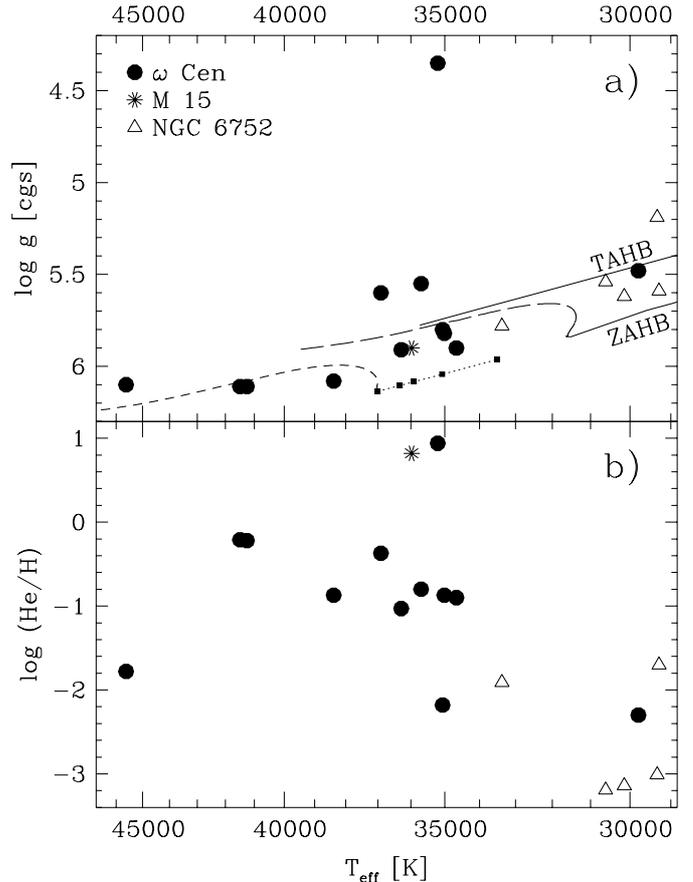


Fig. 4. a) Atmospheric parameters derived from the spectra of blue hook stars in ω Cen compared to HB evolutionary tracks. Also shown are blue tail stars from NGC 6752 (open triangles, Moehler et al. 2000) and the helium-rich sdB star in M 15 (starry symbol, Moehler et al. 1997). The tracks for an early hot flasher (long-dashed line) and a late hot flasher (short-dashed line) show the evolution of such stars from the zero-age HB (ZAHB) towards helium exhaustion in the core (terminal-age HB = TAHB). The solid lines mark the canonical HB locus for $[M/H] = -1.5$ from Sweigart (1997). The dotted line connects the series of ZAHB models computed by adding a hydrogen-rich layer to the surface of the ZAHB model of the late hot flasher. The filled squares mark – with decreasing temperature – hydrogen layer masses of $0, 10^{-7}, 10^{-6}, 10^{-5}, 10^{-4} M_\odot$. b) Helium abundances for the same stars.

canonical EHB stars might populate this gap during their post-ZAHB evolution. To examine this possibility more closely, we plot in Fig. 5 the HB evolutionary tracks from Brown et al. (2001) for 4 canonical stars near the hot end of the EHB and 4 late hot flashers. The latter tracks span the range in RGB mass loss over which flash mixing occurs. Each track is represented by a series of points separated by a time interval of 5×10^6 yr in order to illustrate where the evolution is slowest. Figure 5 shows that canonical EHB stars spend almost their entire HB lifetime at temperatures close to their ZAHB temperatures. While these stars evolve into the temperature gap near the end of the HB phase, they do so at a time when their evolution is very rapid. Thus one would not expect to find many evolved EHB stars within the temperature gap or along the part of the terminal-age HB (TAHB) that extends into the temperature gap

¹ $\log \frac{n_{\text{He}}}{n_{\text{H}}} = -1$.

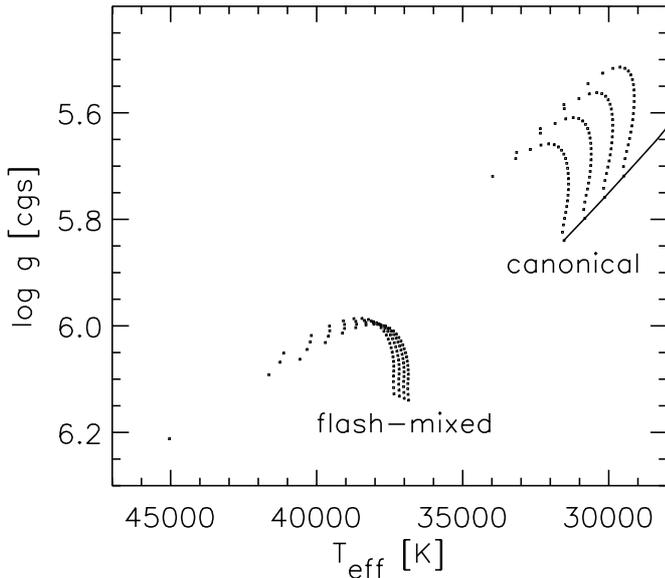


Fig. 5. HB evolutionary tracks for 4 canonical stars near the hot end of the EHB and 4 late hot flashers from Brown et al. (2001). Each track is represented by a series of points separated by a time interval of 5×10^6 yr. The solid line is the canonical ZAHB. Note the temperature gap between the canonical and flash-mixed tracks.

in Fig. 4. We conclude that the flash-mixed stars should remain well separated in temperature from the canonical EHB stars also when HB evolution is taken into account.

Contrary to our original expectations, the atmospheres of the blue hook stars still show some hydrogen. This result may be understood in light of the recent calculations of Schlattl & Weiss (2002, priv. comm.), who found that a small amount of hydrogen survives the flash mixing. The observed atmospheric hydrogen abundance of the blue hook stars is, however, substantially greater than the predicted envelope hydrogen abundance ($X \approx 10^{-4}$) in the models of Schlattl & Weiss after flash mixing. This apparent discrepancy could be readily explained by the outward diffusion of hydrogen into the atmospheres of the blue hook stars and the gravitational settling of helium. Such diffusive processes are believed to be responsible for the low helium abundances of the sdB stars and are estimated to operate on a time scale much shorter than the HB lifetime. The range in the hydrogen abundances of the blue hook stars might indicate that varying amounts of hydrogen survive flash mixing or that the efficiency of diffusion differs from star to star. In any case the high helium abundances observed in some of the blue hook stars would be difficult to understand if their atmospheres were not enriched in helium during the helium flash. The increase in the mean atmospheric helium abundance with increasing effective temperature is also consistent with flash mixing.

The presence of a hydrogen-rich surface layer would shift the evolutionary track for the late hot flasher in Fig. 4 towards cooler temperatures. This evolutionary track, taken from the blue hook sequences of Brown et al. (2001), has a helium/carbon-rich envelope with no hydrogen. In order to estimate the size of this temperature shift, we computed a series of ZAHB models in which hydrogen-rich layers with masses

of 10^{-7} , 10^{-6} , 10^{-5} and $10^{-4} M_{\odot}$ were added to the ZAHB model from the late hot flasher in Fig. 4. A hydrogen layer of $10^{-4} M_{\odot}$ corresponds to the case in which ≈ 10 percent of the envelope hydrogen survives flash mixing and in which all of this hydrogen then diffuses to the surface. This should be a firm upper limit to the mass of any hydrogen layer, given the results of Schlattl & Weiss (2002, priv. comm.) and the fact that any hydrogen present in the deeper layers of the envelope would not have sufficient time to diffuse to the surface during the HB phase. As expected, the ZAHB location of the late hot flasher in Fig. 4 shifts redward as the mass of the hydrogen layer increases and we see that the addition of a hydrogen layer of $< 10^{-4} M_{\odot}$ would actually improve the agreement between the predicted and observed temperatures of the blue hook stars while at the same time preserving the temperature gap between these stars and the canonical EHB stars.

A most intriguing puzzle is posed by D10763, which is the most helium-rich star in our sample: While it is among the faintest stars visually, its low surface gravity suggests a very high luminosity, which would put it to a distance of about 50 kpc for a mass of $0.5 M_{\odot}$. Its heliocentric radial velocity of $+170 \pm 40$ km s $^{-1}$, however, suggests that it is a member of ω Cen. The spectrum also shows no evidence for features from a cool star (e.g., stronger Ca II K line or G band), which might influence the parameter determination from the Balmer lines. We have currently no explanation for this object.

6. Conclusions

The high temperatures and high helium and carbon abundances reported here for the blue hook stars in ω Cen provide general support for the flash-mixing hypothesis of Brown et al. (2001). However, several questions remain.

The CMD of ω Cen of Kaluzny et al. (1997) given in Fig. 1 does not show clear evidence for a gap within the EHB such as was found in NGC 2808 at $M_V \approx +4^m.6$ by Walker (1999) and Bedin et al. (2000). Brown et al. (2001) have shown that the EHB gap in NGC 2808 can be identified with the transition between the canonical and flash-mixed stars. There is a gap at $M_V \approx +4^m$ in Fig. 1, but this gap separates the canonical EHB from blue HB stars and is not related to the hot flasher scenario (D’Cruz et al. 2000). A fuller discussion of the gap between the EHB and blue HB in a number of other globular clusters is given by Piotto et al. (1999). One possible reason for the absence of a clear EHB gap in the ω Cen CMD may be the limited precision of the photometry of Kaluzny et al. (1997), who warn about possible problems at faint magnitudes. Alternatively, the absence of a clear gap may be related to the metallicity spread in ω Cen, although the models of D’Cruz et al. (1996; their Fig. 2) suggest that the temperature at the hot end of the EHB shows little dependence on metallicity. Given the known radial metallicity gradient in ω Cen (e.g. Hilker & Richtler 2000), it would be of interest to determine if there is a gradient in the fraction of EHB stars which are blue hook stars.

Another question is why flash-mixed stars appear in ω Cen and NGC 2808 but not in other EHB clusters such as M 13 and NGC 6752. Both ω Cen ($M_V = -10^m.29$; Harris 1996) and NGC 2808 ($M_V = -9^m.36$) are among the most massive globular

clusters in the Galaxy, so that the observed large EHB population in these clusters is not unexpected. However, the question of why a larger fraction of EHB stars in these clusters should be blue hook stars remains unexplained, and can be considered as another twist in the general problem of understanding the origin of the HB morphologies in globular clusters.

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References

- Bedin, L. R., Piotto, G., Zoccali, M., et al. 2000, *A&A*, 363, 159
- Bergeron, P., Saffer, R. A., & Liebert, J. 1992, *ApJ*, 394, 228
- Brown, T. M., Sweigart, A. V., Lanz, T., Landsman, W. B., & Hubeny, I. 2001, *ApJ*, 562, 368
- Castellani, M., & Castellani, V. 1993, *ApJ*, 407, 649
- D’Cruz, N. L., Dorman, B., & Rood, R. T. 1996, *ApJ*, 466, 359
- D’Cruz, N. L., O’Connell, R. W., Rood, R. T., et al. 2000, *ApJ*, 530, 352
- Fujimoto, M. Y., Iben, I. Jr., & Hollowell, D. 1990, *ApJ*, 349, 580
- Fujimoto, M. Y., Ikeda, Y., & Iben, I. Jr. 2000, *ApJ*, 529, L25
- Hamuy, M., Walker, A. R., Suntzeff, N. B., et al. 1992, *PASP*, 104, 533
- Harris, W. E. 1996, *AJ*, 112, 1487 (version June 22, 1999)
- Herwig, F. 2001, *Stellar Evolution and Nucleosynthesis of Post-AGB Stars*, in *Post-AGB Objects as a Phase of Stellar Evolution*, ed. R. Szczerba, & S. K. Górný, *Astrophys. Space Sci. Lib.* 265 (Boston: Kluwer Academic Publishers), 249
- Hilker, M., & Richtler, T. 2000, *A&A*, 362, 895
- Hollowell, D., Iben, I. Jr., & Fujimoto, M. Y. 1990, *ApJ*, 351, 245
- Horne, K. 1986, *PASP*, 98, 609
- Iben, I. Jr. 1976, *ApJ*, 208, 165
- Iben, I. Jr. 1984, *ApJ*, 277, 333
- Iben, I. Jr. 1995, *Phys. Rep.*, 250, 1
- Iben, I. Jr., Kaler, J. B., Truran, J. W., & Renzini, A. 1983, *ApJ*, 264, 605
- Kaluzny, J., Kubiak, M., Szymański, M., et al. 1996, *A&AS*, 120, 139
- Kaluzny, J., Kubiak, M., Szymański, M., et al. 1997, *A&AS*, 122, 471
- Lemke, M., Heber, U., Napiwotzki, R., Dreizler, S., & Engels, D. 1997, *New Results from the Stellar Component of the Hamburg Schmidt Survey: A Sample of sdO Stars*, in *The Third Conf. on Faint Blue Stars*, ed. A. G. D. Philip, J. Liebert, & R. A. Saffer (Schenectady: L. Davis Press), 375
- Moehler, S., Heber, U., & Durrell, P. 1997, *A&A*, 317, L83
- Moehler, S., Sweigart, A. V., Landsman, W. B., & Heber, U. 2000, *A&A*, 360, 120
- Napiwotzki, R. 1997, *A&A*, 322, 256
- Napiwotzki, R., Green, P. J., & Saffer, R. A. 1999, *ApJ*, 517, 399
- Piotto, G., Zoccali, M., King, I. R., et al. 1999, *AJ*, 118, 1727
- Renzini, A. 1990, *Evolutionary Scenarios for R CrB Stars*, in *Confrontation Between Stellar Pulsation and Evolution*, ed. C. Cacciari, & G. Clementini (San Francisco: ASP), 549
- Saffer, R. A., Bergeron, P., Koester, D., & Liebert, J. 1994, *ApJ*, 432, 351
- Schlattl, H., Cassisi, S., Salaris, M., & Weiss, A. 2001, *ApJ*, 559, 1082
- Sweigart, A. V. 1997, *Helium mixing in globular cluster stars*, in *The Third Conference on Faint Blue Stars*, ed. A. G. D. Philip, J. Liebert, & R. A. Saffer (Schenectady: L. Davis Press), 3
- Sweigart, A. V., Brown, T. M., Lanz, T., Landsman, W. B., & Hubeny, I. 2002, *The Origin of Hot Subluminous Horizontal-Branch Stars in ω Centauri and NGC 2808*, in *ω Centauri: A Unique Window into Astrophysics*, ed. F. van Leeuwen, G. Piotto, & J. Hughes (San Francisco: ASP), 261
- Tüg, H. 1977, *ESOMe*, 11, 7
- Walker, A. R. 1999, *AJ*, 118, 432
- Werner, K. 1996, *ApJ*, 457, L39
- Werner, K., & Dreizler, S. 1999, *The Classical Stellar Atmosphere Problem*, *J. Comp. Appl. Math.*, 109, ed. H. Riffert, & K. Werner (Elsevier Press, Amsterdam), 65
- Whitney, J. H., Rood, R. T., O’Connell, R. W., et al. 1998, *ApJ*, 495, 284