New Views of the Horizontal Branch in $\omega$ Centauri

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Abstract. UV observations of some massive globular clusters uncovered a significant population of very hot stars below the hot end of the horizontal branch, the so-called blue hook stars. This feature might be explained either by the late hot flasher scenario where stars experience the helium flash while on the white dwarf cooling curve or by the helium-rich sub-population recently postulated to exist in some clusters. Previous spectroscopic analyses of blue hook stars in $\omega$ Cen and NGC 2808 support the late hot flasher scenario, but the stars were found to contain much less helium than expected and the predicted carbon and nitrogen enrichment could not be verified. New moderately high resolution spectra of stars at the hot end of the blue horizontal branch in $\omega$ Cen were analysed for atmospheric parameters ($T_{\text{eff}}$, log $g$, and log $n_{\text{He}}/n_{\text{H}}$) and abundances using LTE and non-LTE model atmospheres. In the temperature range 30,000 K to 50,000 K we find that 35% of our stars are helium-poor ($\log n_{\text{He}}/n_{\text{H}} < -2$), 51% have solar helium abundance within a factor of 3 ($-1.5 \leq \log n_{\text{He}}/n_{\text{H}} \leq -0.5$) and 14% are helium-rich ($\log n_{\text{He}}/n_{\text{H}} > -0.4$). We also find carbon enrichment along with helium enrichment, with a maximum carbon abundance of 3% by mass. At least 14% of the hottest horizontal branch stars in $\omega$ Cen show helium abundances well above the highest predictions from the helium enrichment scenario ($Y \approx 0.42$, corresponding to $\log n_{\text{He}}/n_{\text{H}} \approx -0.74$). In addition, the most helium-rich stars show high carbon abundances as predicted by the late hot flasher scenario. We conclude that the helium-rich horizontal branch stars in $\omega$ Cen cannot be explained solely by the helium-enrichment scenario invoked to explain the blue main sequence.
1. Introduction

UV-Visible colour-magnitude diagrams of the two very massive globular clusters, ω Cen and NGC 2808, show stars lying below the canonical extreme horizontal branch (EHB), forming a hook-like feature at its hot end (Whitney et al. 1998; D'Cruz et al. 2000; Brown et al. 2001). Brown et al. (2001) have proposed a “flash-mixing” scenario to explain these blue hook stars. According to this scenario stars which lose an unusually large amount of mass will leave the red giant branch before the helium flash and will move quickly to the (helium-core) white dwarf cooling curve before igniting helium (Castellani & Castellani 1993; D'Cruz, Dorman & Rood 1996; Brown et al. 2001). However, the evolution of these “late hot helium flashers” differs significantly from the evolution of stars which undergo the helium flash on the red giant branch. Ordinarily when a star flashes at the tip of the red giant branch or shortly thereafter, the large entropy barrier of its strong hydrogen-burning shell prevents the products of helium burning from being mixed to the surface. Such canonical stars will evolve to the zero-age horizontal branch (ZAHB) without any change in their hydrogen-rich envelope composition. In contrast, stars that ignite helium on the white dwarf cooling curve, where the hydrogen-burning shell is much weaker, will undergo extensive mixing between the helium- and carbon-rich core and the hydrogen envelope (Sweigart 1997; Brown et al. 2001; Cassisi et al. 2003). Depending on where the helium flash occurs along the white dwarf cooling curve, the envelope hydrogen will be mixed either deeply into the core (“deep mixing”) or only with a convective shell in the outer part of the core (“shallow mixing”). In the case of deep mixing almost all hydrogen in the envelope is burned while in the case of shallow mixing some of the envelope hydrogen remains after the mixing phase (Lanz et al. 2004). One of the most robust predictions of the flash-mixing scenario is an increase in the surface abundance of carbon by mass to 3% - 5% (deep mixing) or 1% (shallow mixing). This increase is set by the carbon production during the helium flash and is nearly independent of the stellar parameters. Nitrogen may also be enhanced due to the burning of hydrogen on triple-α carbon during the flash-mixing phase. For both deep and shallow mixing, the blue hook stars should be helium-rich compared to the canonical EHB stars.

Alternatively, the recently observed split among the main sequence stars of ω Cen and NGC 2808 (Bedin et al. 2004; Piotto et al. 2005, 2007) has been attributed to a sub-population of stars with helium abundances as large as Y≈0.4 (Norris 2004; D’Antona et al. 2005; D’Antona & Ventura 2007; see Newsham & Terndrup (2007) for cautionary remarks). Lee et al. (2005) have suggested that the blue hook stars are the progeny of these proposed helium-rich main sequence stars. In this case their helium abundance should not exceed Y≈0.4. Spectroscopic observations of the blue (and supposedly helium-rich) main sequence stars in ω Cen yield a carbon abundance of [C/M] = 0.0 (Piotto et al. 2005). This carbon abundance will decrease further as the stars ascend the red giant branch, due to the extra-mixing process that occurs in metal-poor red giants (Gratton et al. 2000; Kraft 1994). Origlia et al. (2003) have confirmed that the red giant branch stars in ω Cen have the low $^{12}$C/$^{13}$C ratios ($\approx$4) and low average carbon abundances ([C/Fe] = −0.2) expected from this extra mixing. Thus the helium-enrichment scenario predicts a carbon abundance by mass in
the blue hook stars of less than 0.1%, i.e., at least a factor of 10 smaller than the carbon abundance predicted by the flash-mixing scenario.

Previous spectra of the blue hook stars in ω Cen (Moehler et al. 2002) and NGC 2808 (Moehler et al. 2004) showed that these stars are indeed both hotter and more helium-rich than the canonical EHB stars. However, the blue hook stars still show considerable amounts of hydrogen. Unfortunately due to limited resolution and signal-to-noise (S/N) we could not derive good abundances for C and N. Instead we could only state that the most helium-rich stars appear to show some evidence for C/N enrichment. Therefore we started a project to obtain higher resolution spectra of EHB and blue hook stars in ω Cen.

2. Observations, Data Reduction, and Analysis

![Graph showing effective temperatures and surface gravities](image)

Figure 1. Here we show the effective temperatures and surface gravities derived for our hottest target stars (formal errors only). Helium-poor, solar helium, and helium-rich stars are marked by open, gray, and black squares, respectively. The solid lines mark the canonical horizontal branch locus for [M/H] = −1.5 from Moehler et al. (2003). 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 horizontal branch (ZAHB) towards helium exhaustion in the core (terminal-age HB = TAHB). 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 small dots mark — with decreasing temperature — hydrogen layer masses of $0, 10^{-7}, 10^{-6}, 10^{-5}, 10^{-4} M_\odot$ (for details see Moehler et al. 2002).

We selected stars along the blue horizontal branch in ω Cen from the multi-band ($U, B, V, I$) photometry of Castellani et al. (2007). These data were col-
lected with the mosaic CCD camera Wide Field Imager available at the 2.2m ESO/MPI telescope. The field of view covered by the entire mosaic is $42' \times 48'$ across the center of the cluster. These data together with multiband data from the Advanced Camera for Surveys on board the Hubble Space Telescope provided the largest sample of horizontal branch stars ($\approx 3,200$) ever collected in a globular cluster. Among them we concentrated on the stars at the faint end of the horizontal branch, which are the most likely “blue hook” candidates as shown by Moehler et al. (2002, 2004). In order to avoid crowding problems, we only selected isolated EHB stars. The astrometry was performed using the UCAC2 catalog (Zacharias et al. 2004), which does not cover the central crowded regions. However, thanks to the large field covered by current dataset the astrometric solution is based on $\approx 3,000$ objects with an rms error of $0''.06$.

The spectroscopic data were obtained in 2005 and 2006 (4 and 5 observations, respectively) in Service Mode using the MEDUSA mode of the multi-object fibre spectrograph FLAMES+GIRAFFE on the UT2 Telescope of the VLT. We used the spectral range 3964 Å – 4567 Å (LR2, $R = 6400$) and observed spectra for a total of 101 blue hook and canonical blue HB/EHB star candidates and 17 empty positions for sky background.

For our analysis we used the pipeline-reduced data. For each exposure we subtracted the median of the spectra from the sky fibres from the extracted spectra. We corrected all spectra for barycentric motions. The individual spectra of each target star have been cross-correlated with appropriate template spectra, in order to search for radial velocity variations. We determined the standard deviation of the radial velocity measurements for each star and found that it decreases with increasing S/N ratio. None of our target stars deviates significantly from this correlation, which would be the case for close binaries. Therefore none of our target stars appears to be in a close binary system. After verifying that there were no radial velocity variations we co-added all spectra for each star. The co-added and velocity-corrected spectra were fitted with various model atmospheres: metal-free helium-rich non-LTE (Werner & Dreizler 1999), metal-free helium-poor non-LTE (Napiwotzki 1997), and metal-rich helium-poor LTE (Moehler et al. 2000) as described in Moehler et al. (2004). This procedure yielded the effective temperatures, surface gravities, and helium abundances shown in Figs. 1 and 2. In this paper we concentrate only on the hottest horizontal branch stars with $T_{\text{eff}}>20,000$ K.

3. Results and Discussion

The helium-poor stars in Fig. 1 basically agree with the predictions of canonical evolutionary theory in that they populate the horizontal branch up to its hot end and then also contribute some evolved stars at higher effective temperatures and lower surface gravities. As we move to hotter stars ($T_{\text{eff}} \geq 30,000$ K), we find a clump of stars populating the range in effective temperature and surface gravity between a fully mixed late hot flasher and the hot edge of the canonical extreme horizontal branch. These stars show roughly solar helium abundance (cf. Fig. 2). The hottest stars lying along the evolutionary track of a fully mixed late hot flasher show the highest helium abundances, albeit with still some hydrogen in their atmospheres. In the temperature range $30,000$ K to $50,000$ K we find
Figure 2. Here we show the effective temperatures and helium abundances for our hottest target stars (formal errors only). The dashed line marks solar helium abundance, the hashed area marks the range for the helium-enrichment scenario. The symbols have the same meaning as in Fig. 1.

that 35% (15) of our stars are helium-poor ($\log \frac{n_{\text{He}}}{n_{\text{H}}} < -2$), 51% (22) have solar helium abundance within a factor of 3 ($-1.5 \leq \log \frac{n_{\text{He}}}{n_{\text{H}}} \leq -0.5$) and 14% (6) are helium-rich ($\log \frac{n_{\text{He}}}{n_{\text{H}}} > -0.4$).

The helium-rich stars also show evidence for carbon enrichment as shown in Fig. 3. The hot ($T_{\text{eff}} > 30,000$ K) helium-poor stars, on the other hand, show no detectable C II and C III lines despite the higher S/N in their spectra. We have constructed additional NLTE line-blanketed model atmospheres with TLUSTY (Hubeny & Lanz 1995), adopting the basic parameters (effective temperatures, surface gravities, and helium abundances) that were derived earlier. The model atmospheres allow departures from LTE for 1132 explicit levels and superlevels of 52 ions (H, He, C, N, O, Ne, Mg, Al, Si, P, S, Fe; see Lanz & Hubeny (2003, 2007) for more details). For these models we assumed either scaled-solar abundances appropriate for the dominant $\omega$ Cen metallicity ([M/H] = −1.5) or the carbon- and nitrogen-rich abundances predicted by the flash mixing scenario (mass fractions of 3% and 1%, respectively). The comparison between observed and predicted C II and C III lines indicates that the helium-rich stars have a photospheric carbon mass fraction of at least 1% and up to 2–3% for the stars with the strongest lines. The typical line detection limit provides an upper limit of about 1% by mass for the nitrogen abundance. These carbon abundances represent a significant enhancement relative to the expected carbon abundance in $\omega$ Cen stars (≤0.1% by mass at most for the most metal-rich stars).

Any discussion of the surface abundances in hot horizontal branch stars must consider the effects of diffusion. Fortunately the diffusion of H, He and
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Figure 3. Here we show sample spectra of stars with super-solar helium abundance (light gray), compared to model spectra with the cluster carbon abundance for metal-poor stars (dark gray) and a carbon abundance of 3% by mass (black). The labels give the number of the star, its effective temperature, and its helium abundance \( \log \frac{n_{\text{He}}}{n_\text{H}} \).

the CNO elements in the envelopes of stars following deep flash mixing has been investigated by Unglaub (2005). Not surprisingly, the results depend on the assumed mass loss rate and on the hydrogen abundance remaining after the flash mixing. For the low residual hydrogen abundance \( X = 0.0004 \) predicted by the Cassisi et al. (2003) models, Unglaub (2005) found that a star will remain helium-rich with \( \log \frac{n_{\text{He}}}{n_\text{H}} \approx 0 \ldots 2 \) during most of the horizontal branch phase, in rough agreement with the helium-rich stars in Fig. 2. However, the residual hydrogen abundance following flash mixing is quite uncertain, since it depends on the mixing efficiency (Cassisi et al. 2003) and possibly on where the helium flash occurs along the white dwarf cooling curve. For a larger, but still low, residual hydrogen abundance of \( X = 0.004 \), Unglaub (2005) found that diffusion can produce either a star with near solar helium abundance or a star that is helium-poor by the end of its horizontal branch phase. The stars with roughly solar helium abundances in Fig. 2 might be a consequence of such diffusion.

The ZAHB models with a hydrogen-rich layer in Fig. 1 show that the effective temperature will decrease as the amount of surface hydrogen increases in qualitative agreement with the trend towards lower effective temperatures between the helium-rich stars and solar helium abundance stars in Fig. 2. Unglaub (2005) also noted that the diffusion efficiency increases substantially once the
helium abundance approaches the solar value, leading to a rapid decrease in helium abundance and perhaps accounting for the gap between the solar helium stars and helium-poor stars in Fig. 2. Diffusion in flash-mixed stars also leads to a decrease in the carbon and nitrogen abundances, which becomes more pronounced when the atmosphere becomes hydrogen-rich. Thus the carbon abundances derived here for the helium-rich stars may underestimate the initial carbon abundances in these stars.

A puzzling effect becomes evident if one plots the spatial distribution of our target stars (see Fig. 4): While the helium-poor stars are evenly distributed, the stars with roughly solar or super-solar helium abundance show a noticeable preference for the north-west section of the globular cluster. This distribution appears similar to the reddening distribution observed by Calamida et al. (2005), who found a clumpy extinction variation with less reddened horizontal branch stars concentrated on the east side of the cluster (see their Fig. 5).

4. Conclusions

All these results offer strong support for the late hot flasher scenario as the explanation for the blue hook stars while posing a significant problem for the helium-enrichment scenario. This scenario predicts helium enrichment of up to $Y = 0.35 \ldots 0.42$, i.e. $\log \frac{n_{\text{He}}}{n_{\text{H}}} = -0.87 \ldots -0.74$. However, 40% – 30% of the stars above 30,000 K show helium abundances in excess of these values, respectively. In view of the high efficiency of diffusion one would expect any helium-rich star on the main sequence to have much a lower helium abundance.
on the EHB. This result together with the observed carbon enhancement does not rule out the helium enhancement scenario, but it implies that additional processes are required to produce the hottest horizontal branch stars in ω Cen.

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References