Helium-rich EHB Stars in Globular Clusters

S. Moehler (moehler@astrophysik.uni-kiel.de)
Institut für Theoretische Physik und Astrophysik der Universität Kiel, Abteilung Astrophysik, 24098 Kiel, Germany

A.V. Sweigart and W.B. Landsman
NASA Goddard Space Flight Center, Code 681, Greenbelt, MD 20771, USA

S. Dreizler
Astronomisches Institut der Universität Tübingen, Sand 1, D-72076 Tübingen, Germany

Abstract. Recent UV observations of the most massive Galactic globular clusters show a significant population of hot stars below the zero-age HB (“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. They should show higher temperatures than the hottest canonical HB stars and their atmospheres should be helium-rich and probably C/N-rich. We have obtained spectra of blue hook stars in ω Cen and NGC 2808 to test this possibility. Our analysis shows that the blue hook stars in these clusters reach effective temperatures well beyond the hot end of the canonical EHB and have higher helium abundances than canonical EHB stars. These results support the hypothesis that the blue hook stars arise from stars which ignite helium on the white dwarf cooling curve.

Keywords: Globular Clusters

1. Introduction

Low-mass stars burning helium in a core of about 0.5 M⊙ and hydrogen in a shell populate a roughly horizontal region in the colour-magnitude diagrams of globular clusters, which has earned them the name “horizontal branch” (HB) stars. The Galactic globular clusters show a great variety in horizontal branch morphology, i.e. in the temperature distribution of their HB stars. The temperature of an HB star depends – at a given metallicity – on the mass of its envelope, with the hottest or extreme HB (EHB) stars (T_{eff} > 20,000 K) having extremely thin (<0.01 M⊙) envelopes. For stars hotter than about 10,000 K the increase in the bolometric correction with increasing temperature turns the blue HB into a vertical blue tail in optical colour-magnitude diagrams, with the faintest blue tail stars being the hottest and least massive. EHB stars are in general fainter than M_V ≈ +4m and thus

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most of the stars along the blue tails are classical hot horizontal branch stars.

Observations of some of the most massive Galactic globular clusters in the far- and near-UV (ω Cen, Whitney et al. 1998, D’Cruz et al. 2000; NGC 2808, Brown et al. 2001; NGC 6388, NGC 6441, Busso et al. 2003) show a group of stars forming a hook-like feature up to 0\"m7 below the hot end of the zero-age HB (ZAHB). Within the framework of canonical HB theory there is no way to populate this region of the UV colour-magnitude diagram without requiring an implausibly large decrease in the helium-core mass.

Optical colour-magnitude diagrams of these globular clusters show that the blue hook stars lie at the very faint and hot end of the blue tails (M_V \approx 4^{m}5–5^{m}5). 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 (which are all brighter than M_V \approx 4^{m}5) 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.

Stars which lose a large amount of mass on the red giant branch can leave the red giant branch without experiencing the helium flash, and move quickly to the (helium-core) white dwarf cooling curve. 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”), either during the evolution to the top of the white dwarf cooling curve (“early hot flashers”) or while descending the white dwarf cooling curve (“late 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 \approx0^{m}1 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 with regard to the timing of the flash. Their models show that a late hot helium flash on the white dwarf cooling curve will induce substantial mixing between the hydrogen envelope and the helium core, leading to helium-rich EHB stars that are much hotter than canonical ones. They 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 flash mixing scenario predicts a helium dominated atmospheric composition for the late hot flashers as well as a gap of about 6000 K between the late hot flashers and canonical EHB stars (i.e. EHB stars which have
not experienced flash mixing and which therefore have hydrogen-rich atmospheres).

2. Observations and Data Reduction

We obtained medium-resolution spectra \( (R \approx 700) \) of 12 blue hook candidates in \( \omega \) Cen with \( 18.5 < V < 19.2 \) at the NTT with EMMI on February 22–25, 2001 and medium-resolution spectra \( (R \approx 900) \) of 19 stars along the blue tail in NGC 2808 with \( 19^m < V < 21^m \) at the VLT-UT1 (Antu) with FORS1 in service mode. The data reduction for the \( \omega \) Cen data is described in Moehler et al. (2002). The data reduction for the NGC 2808 data will be described in Moehler et al. (2003). The spectra, given in Fig. 1, show a large variety of helium line strengths. Part of this variation is due to variations in effective temperature, which is evident from the varying strength of the Balmer absorption lines. However, as we will see in the analysis, the helium abundance also varies considerably.

3. Analysis

To obtain effective temperatures, surface gravities and helium abundances we fitted the spectra with theoretical model spectra. For hot stars \( (T_{\text{eff}} \gtrsim 33,000 \, \text{K}) \) we used non-LTE H-He model atmospheres as described in Moehler et al. (2002). For the cooler stars we used ATLAS9 line blanketed LTE model atmospheres for solar metallicity (to account for effects of radiative levitation), from which we calculated spectra with Lemke’s version\(^1\) of the LINFOR program (developed originally by Holweger, Steffen, and Steenbock at Kiel University). 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 \( \chi^2 \) test. The \( \sigma \) necessary for the calculation of \( \chi^2 \) is estimated from the noise in the continuum regions of the spectra. The fit program normalizes model spectra \textit{and} observed spectra using the same points for the continuum definition. During the analysis of the data presented here we realized that helium-poor and helium-rich spectra required different sets of continuum points. Especially the use of the continuum points derived from hydrogen-rich spectra for the analysis of helium-rich spectra can introduce large systematic errors, esp. overestimates of the helium abundance due to continuum points in the wings of strong

\(^1\) For a description see http://a400.sternwarte.uni-erlangen.de/~ai26/linfit/linfor.html
Figure 1. Our spectra of blue tail/blue hook stars in ω Cen (WF3–1 was identified as a target in the HST photometry of D’Cruz et al. 2000, all other numbers refer to the photometry from Kaluzny et al. 1996,1997) and NGC 2808 (numbers refering to the photometry of Walker 1999). The dotted lines mark the position of the He i lines, the dashed line marks the He ii line at 4686 Å.
helium lines and/or too narrow fitting windows for helium lines. We therefore refined the definition of the continuum points and re-analysed the data for the blue hook stars in ω Cen presented in Moehler et al. (2002). The new results differ from the old ones usually within the mutual error bars, except for the two most helium-rich stars, as expected.

We used the Balmer lines H$_{\beta}$ to H$_{\gamma}$ (excluding H$_{\epsilon}$ to avoid the Ca II H line), the He I lines λλ 4026 Å, 4388 Å, 4471 Å, 4921 Å and the He II lines λλ 4542 Å, 4686 Å for the helium-poor stars. For the helium-rich
Moehler et al. stars we also included the He I lines $\lambda\lambda$ 4713 Å, 5015 Å and 5044 Å in the fit. The results are plotted in Figs. 2 and 3.

![Figure 3](image-url)

**Figure 3.** Helium abundances vs. effective temperature for the stars along the blue tail/blue hook in NGC 2808 (filled squares) and ω Cen (open squares). Also shown are blue tail stars from NGC 6752 (open triangles, Moehler et al. 2000). Solar helium abundance corresponds to $\log n_{\text{He}}/n_{\text{H}} \approx -1$.

4. Discussion

Our analysis of the blue hook stars in NGC 2808 and ω Cen shows that these stars do indeed reach effective temperatures of more than 35,000 K (cf. Fig. 2), well beyond the hot end of the canonical EHB. In addition, most of the hot stars show at least solar helium abundances with the helium abundance increasing with effective temperature (cf. Fig. 3), 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.

Contrary to the predictions of Brown et al. (2001) and Cassisi et al. (2003), the atmospheres of the blue hook stars still show some hydro-
gen. This result has been discussed by Cassisi et al. (2003), who find that the mixing efficiency must be reduced by a factor of about 20,000 in order to reproduce even the highest helium abundances observed by Moehler et al. (2002). However, this reduction only applies if the observed helium abundances reflect the actual helium abundances in the envelopes of the blue hook stars.

The remaining hydrogen could be possibly 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. It is unclear, however, whether diffusion might be inhibited to some extent by convection within the helium-enriched atmospheres of the flash-mixed stars. Groth et al. (1985) found that atmospheric convection can exist in hot subdwarfs if the helium abundance is sufficiently high. The range in the hydrogen abundances of the blue hook stars might therefore 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. 3 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. 2. A hydrogen layer of $10^{-4} \, M_\odot$ corresponds to the case in which $\approx10\%$ of the envelope hydrogen survives flash mixing and in which all of this hydrogen then diffuses to the surface. As expected, the ZAHB location of the late hot flasher in Fig. 3 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. While the HB track for the early hot flasher in Fig. 2 passes through the temperature gap, stars evolve very fast along this part of the track and the probability to find evolved stars in that region is very low.
We therefore conclude that the high temperatures and high helium abundances reported here for the blue hook stars in NGC 2808 and ω Cen provide general support for the flash-mixing hypothesis of Brown et al. (2001).

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References

Bedin, L.R., Piotto, G., Zoccali, M., Stetson, P.B., Saviane, I., Cassisi, S., Bono, G. 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
Busso, G., Piotto, G., Cassisi, S. 2003, HST multiband photometry of the globular cluster NGC 6388, to appear in MemSAI
Cassisi, S., Schlattl, H., Salaris, M., Weiss, A. 2003, ApJ, 582, L43
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
Groth H.G., Kudritzki R.P., Heber U. 1985, A&A 152, 107
Kaluzny, J., Kubiak, M., Szymański, M., Udalski, A., Krzemiński, W., Mateo, M. 1996, A&AS, 120, 139
Kaluzny, J., Kubiak, M., Szymański, M., Udalski, A., Krzemiński, W., Mateo, M., Stanek, K. 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 Conference on Faint Blue Stars, ed. A.G.D. Philip, J. Liebert & R.A. Saffer (Schenectady: L. Davis Press), 375
Moehler, S., Sweigart, A.V., Landsman, W.B., Heber, U. 2000, A&A, 360, 120
Moehler, S., Sweigart, A.V., Landsman, W.B., Dreizler, S., 2002, A&A 395, 37
Moehler, S., Sweigart, A.V., Landsman, W.B., Dreizler, S., 2003, in prep.
Napiwotzki, R., Green, P.J., Saffer, R.A. 1999, ApJ, 517, 399
Paczynski, B., 1971, AcA 21, 1
Saffer, R.A., Bergeron, P., Koester, D., Liebert, J. 1994, ApJ, 432, 351
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
Walker, A.R. 1999, AJ, 118, 432
Whitney, J.H., Rood, R.T., O'Connell, R.W., et al. 1998, ApJ, 495, 284