

## Extremely Faint Blue-tail Stars in $\omega$ Centauri

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**Abstract.**  $\omega$  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 stars show higher temperatures than the hottest canonical HB stars and have helium- and carbon-rich atmospheres. We obtained and analyzed medium resolution spectra of a sample of “blue hook” stars to derive their atmospheric parameters. We find that the “blue hook” stars are indeed both hotter ( $T_{\text{eff}} \geq 35,000$  K) and more helium-rich than classical extreme HB stars.

Based on observations collected at the European Southern Observatory, Chile (ESO proposal 66.D-0199(A))

### 1. Introduction

Horizontal branch (HB) stars burn helium in a core of about  $0.5M_{\odot}$  and hydrogen in a shell. They have hydrogen-rich envelopes of varying mass and the more massive the envelope, the cooler is the HB star. HB stars with envelope masses below  $0.02M_{\odot}$  do not have active hydrogen-burning shells (extreme HB stars = EHB stars) and can be identified with the subdwarf B stars in the field of the Milky Way, which are considered good candidates for the cause of the UV excess in elliptical galaxies. The increase in bolometric correction with increasing temperature turns the horizontal branch into a vertical blue tail (in optical color-magnitude diagrams) with the faintest blue tail stars being the hottest and least massive ones.

The globular cluster  $\omega$  Cen shows a large number of hot horizontal branch stars that populate a very long blue tail down to rather faint visual magnitudes. Observations of  $\omega$  Cen in the far-UV (Whitney et al. 1998; D’Cruz et al. 2000) revealed a puzzling feature: At the very hot end the HB shows a spread in UV brightness that cannot be explained by measuring errors. While stars brighter than the zero-age HB (ZAHB) might be understood by evolution away from the ZAHB, the stars fainter than the ZAHB cannot be explained by canonical HB evolution. The fainter stars appear to form a hook-like feature extending up to 0.7 mag below the ZAHB and are therefore called “blue hook” stars. In the optical color-magnitude diagram these stars show up at the very faint end of the blue tail (cf. Fig. 1.), in agreement with their high temperatures suggested by the UV photometry.

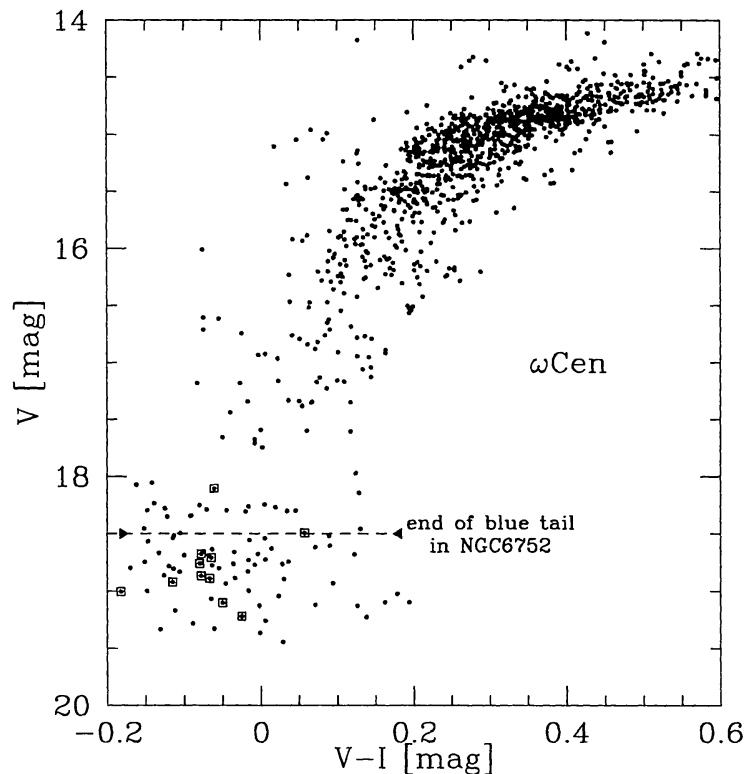


Figure 1. Colour-magnitude diagram of the blue tail of  $\omega$  Cen (Kaluzny et al. 1997) with the spectroscopic targets marked. Also given is the magnitude of the faint end of the blue tail in NGC 6752 transformed to  $\omega$  Cen by adjusting for the difference in  $(m - M)_V$  of 0.7 mag.

The “blue hook” stars populate a range in absolute visual magnitude that extends beyond the limit of the blue tail in NGC 6752, which has been studied extensively by 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 extreme HB to the hot end predicted by canonical HB models (cf. Fig. 2).

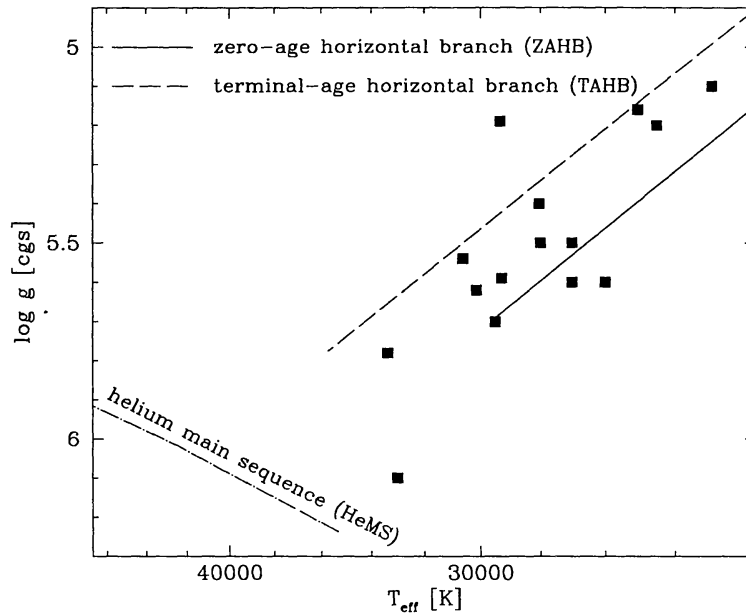


Figure 2. Observed parameters for hot stars in NGC 6752 (Moehler et al. 2000) compared to the canonical HB locus for  $[M/H] = -1.5$  from Sweigart (1997). The helium main sequence is taken from Paczynski (1971).

Even hotter EHB stars cannot be produced by simply reducing their envelope mass, since a minimum mass of the hydrogen envelope is required for canonical models to initiate the helium core flash (see, e.g., Brown et al. 2001). Obviously other evolutionary channels are needed.

## 2. Delayed Helium Flash

Castellani & Castellani (1993) were the first to suggest that – for extremely high mass loss on the red giant branch (RGB) – the helium core flash can occur at high temperatures after the star has left the RGB and started its evolution into a helium-core white dwarf (“hot flasher”). D’Cruz et al. (1996; 2000) proposed that the “blue hook” stars could be the product of such “hot flashers”.

Brown et al. (2001) studied the “hot flasher” scenario in more detail, especially with respect to the timing of the flash. They found that a flash above the top of the helium-core white dwarf cooling curve (before the “knee” visible in Fig. 3) yields helium core masses  $\leq 0.001 M_{\odot}$  below those of cooler EHB stars, implying no change in the predicted EHB luminosity. The flash convection zone in these “early hot flashers” does not penetrate the hydrogen envelope and thus these models are similar to the models of D’Cruz et al. (1996) with effective temperatures of 30,000 K – 35,000 K (see Fig. 3, dotted line) and a hydrogen-rich surface composition. Such stars may populate the clump seen in the UV color-magnitude diagram of  $\omega$  Cen at  $m_{160} - V < -3.0$  and  $14.8 < m_{160} < 15.3$  (D’Cruz et al. 2000), but are too bright for the blue hook.

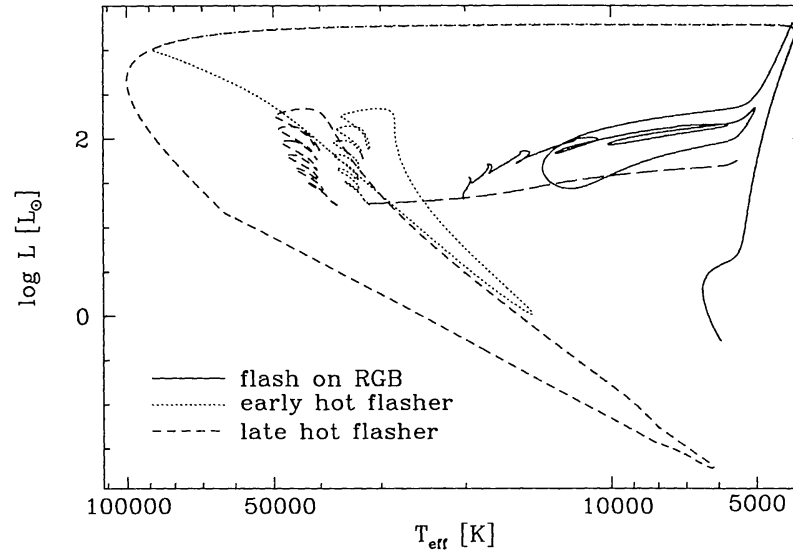


Figure 3. Evolutionary tracks through the helium flash for a star which ignites helium on the RGB (solid line), an “early hot flasher” (dotted line), and a “late hot flasher” (short dashed line). All tracks are taken from Sweigart (1997). The long dashed line marks the canonical zero-age HB (ZAHB).

However, if the flash happens along the helium-core white dwarf cooling curve (“late hot flasher”) the flash convection zone may penetrate the hydrogen envelope due to the weakened hydrogen burning shell. In that case hydrogen from the envelope is mixed to the core, while helium and carbon from the core are transported to the surface. Unfortunately the detailed calculation of this mixing is greatly complicated by the similar timescales of the mixing and nucleosynthesis. The process is similar to the very late helium shell flash that is supposedly responsible for the production of “born-again” H-deficient post-AGB stars. Due to the mixing the surface composition of the “late hot flashers” changes from hydrogen-rich to helium/carbon-rich, which reduces the UV flux due to the very different opacities of helium/carbon vs. hydrogen and to the simultaneous increase in the effective temperature to about 40,000 K (see Fig. 3, short dashed line). This large temperature difference between the “early” and “late hot flashers” in Fig. 3 should produce a gap in the observed temperature distribution towards the hot end of the blue tail.

### 3. Observations and Results

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  $\omega$  Cen. From such observations not only the surface composition (hydrogen-rich as opposed to helium/carbon-rich) can be determined, but also effective temperature and surface gravity. We obtained medium-resolution spec-

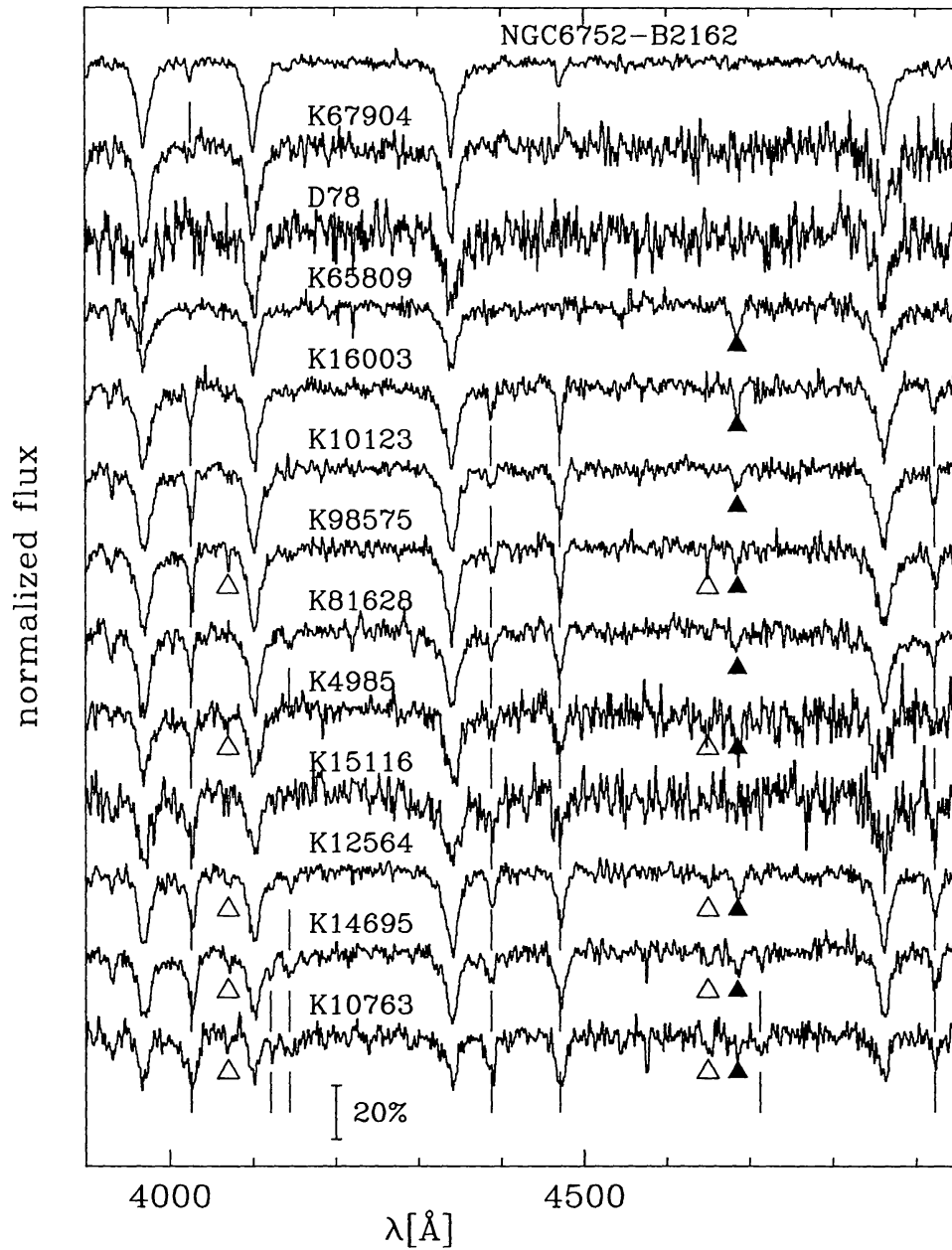


Figure 4. Spectra of blue hook stars in  $\omega$  Cen. For comparison the spectrum of a star at the faint end of the blue tail in NGC 6752 is shown. The lines mark the position of the He I lines, the filled triangles mark the He II line at  $4686\text{\AA}$ , the open triangles mark the C III lines at  $4070\text{\AA}$  and the C III/N III lines at  $4650\text{\AA}$ .

tra ( $R \approx 700$ ) of 12 “blue hook” candidates with  $18.5 < V < 19.2$  at the NTT with EMMI on February 22–25, 2001. The targets were mainly selected from UIT (Whitney et al. 1998) and optical (Kaluzny et al. 1997) photometry.

The data were reduced in the same way as described in Moehler et al. (2000) and the resulting spectra are plotted in Fig. 4.

In contrast to the somewhat brighter (in absolute visual magnitude) blue tail stars analyzed in NGC 6752, which are helium deficient and show weak to no helium lines (cf. Moehler et al. 2000 and uppermost spectrum in Fig. 4), most of the “blue hook” stars in  $\omega$  Cen show rather strong He I lines, and some of them even show C III/NIII and He II absorption (see Fig. 4).

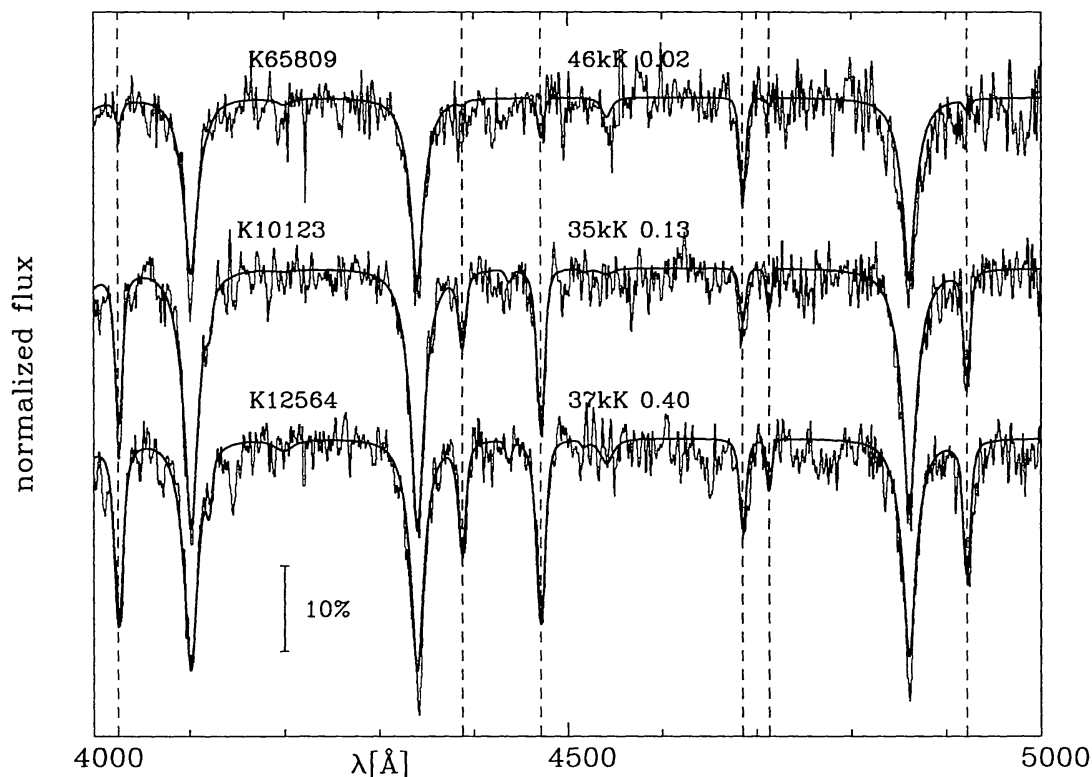


Figure 5. Example fits of some “blue hook” spectra with the He I lines marked. Given are the resulting effective temperature and helium abundance ( $n_{\text{He}}/n_{\text{H}}$ ) for each fit.

Fits to the spectra with non-LTE model atmospheres allow to derive effective temperature, surface gravity, and helium abundance. Nine of the twelve stars show at least solar helium abundance (as opposed to the hottest EHB stars in NGC 6752, which show helium abundances of  $\leq 0.1$  solar, Moehler et al. 2000) and four have a helium abundance by particle number of  $\geq 0.4$  (corresponding to  $Y \geq 0.7$ ). The only other globular cluster blue tail star which has been found to show a supersolar helium abundance is M15 F2-2 (Moehler et al. 1997), which is also quite hot ( $T_{\text{eff}} \approx 35,000$  K).

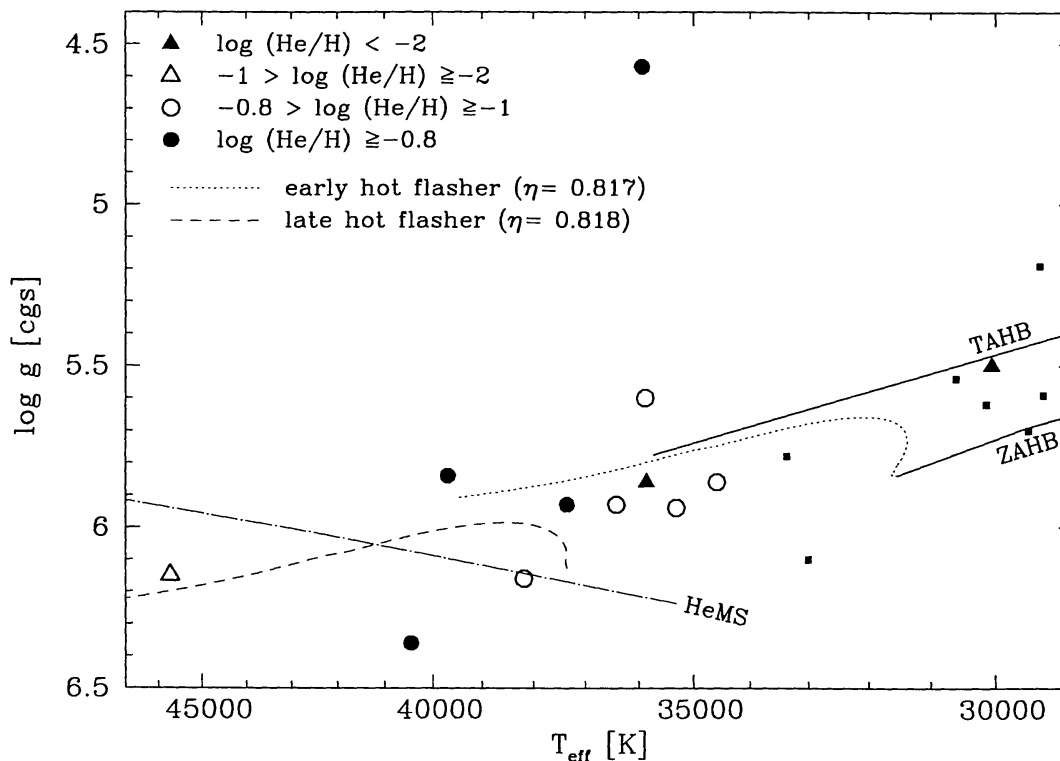


Figure 6. Atmospheric parameters derived from the spectra of “blue hook” stars in  $\omega$  Cen compared to HB evolutionary tracks. Also shown are blue tail stars from NGC 6752 (small filled squares). The tracks for “early” and “late hot flasher” show the evolution of such stars from the zero-age HB towards helium exhaustion in the core (TAHB). For more details about the tracks see Figs. 2 and 3.

A comparison to evolutionary tracks (Fig. 6) shows that the “blue hook” stars are hotter than the hot end of the canonical HB, but cooler than the “late hot flasher” tracks.

#### 4. Conclusions

Our analysis of the “blue hook” stars in  $\omega$  Cen shows that these stars do indeed reach effective temperatures of more than 35,000 K, 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 (in contrast to canonical EHB stars like the ones analyzed in NGC 6752).

However, the atmospheres still show some hydrogen, in contrast to expectations if flash mixing should destroy all hydrogen. It is currently unclear whether small amounts of residual hydrogen might survive the flash mixing and then be enhanced in the observed atmospheric layers by diffusion processes. We also don’t find the gap in effective temperature, that is expected from the large temperature difference between the “early” and “late hot flasher”, which are

separated by a minuscule change in Reimers mass loss parameter  $\eta$ . However, this gap might be obscured by the metallicity spread of  $\omega$  Cen or possibly also by the remaining hydrogen in the atmosphere.

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