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Letter to the Editor

Physical parameters of hot horizontal-branch stars in NGC 6752: deep mixing and radiative levitation

S. Moehler[1,⋆], A.V. Sweigart[2], W.B. Landsman[3], U. Heber[1], and M. Catelan[2,⋆⋆,⋆⋆⋆]

[1] Dr. Remeis-Sternwarte, Astronomisches Institut der Universität Erlangen-Nürnberg, Sternwartstrasse 7, D-96049 Bamberg, Germany (moehler, heber@sternwarte.uni-erlangen.de)
[2] NASA Goddard Space Flight Center, Code 681, Greenbelt, MD 20771, USA (sweigart@bach.gsfc.nasa.gov, catelan@stars.gsfc.nasa.gov)
[3] Raytheon ITSS, NASA Goddard Space Flight Center, Code 681, Greenbelt, MD 20771, USA (landsman@mpb.gsfc.nasa.gov)

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Abstract. Atmospheric parameters ($T_{\rm eff}$, $\log\,g$ and $\log\frac{n_{\rm He}}{n_{\rm H}}$) are derived for 42 hot horizontal branch (HB) stars in the globular cluster NGC 6752. For 19 stars Mg II and Fe II lines are detected indicating an iron enrichment by a factor 50 on average with respect to the cluster abundance whereas the magnesium abundances are consistent with the cluster metallicity. This finding adds to the growing evidence that radiative levitation plays a significant role in determining the physical parameters of blue HB stars. Indeed, we find that iron enrichment can explain part, but not all, of the problem of anomalously low gravities along the blue HB. Thus the physical parameters of horizontal branch stars hotter than about $11{,}500$ K in NGC 6752, as derived in this paper, are best explained by a combination of helium mixing and radiative levitation effects.

Key words: stars: early-type – stars: fundamental parameters – stars: horizontal-branch – Galaxy: globular clusters: individual: NGC 6752

1. Introduction

The discovery of "gaps" along the blue horizontal branch (HB) in globular clusters as well as of long extensions towards higher temperatures has triggered several spectroscopic investigations (Moehler 1999 and references therein) yielding the following results:

1. Most of the stars analysed above and below any gaps along the blue horizontal branch are "bona fide" blue HB stars ($T_{\rm eff} < 20,000$ K), which show significantly lower gravities than expected from canonical stellar evolution theory.
2. Only in NGC 6752 and M 15 have spectroscopic analyses verified the presence of stars that could be identified with the subdwarf B stars known in the field of the Milky Way ($T_{\rm eff} > 20,000$ K, $\log\,g > 5$). In contrast to the cooler blue HB (BHB) stars the gravities of these "extended HB" (EHB) stars agree well with the expectations of canonical stellar evolution.

Two scenarios have been suggested to account for the low gravities of BHB stars:

Helium mixing scenario: Abundance anomalies observed in red giant branch (RGB) stars in globular clusters (e.g., Kraft 1994, Kraft et al. 1997) may be explained by the dredge-up of nuclearly processed material to the stellar surface. If the mixing currents extend into the hydrogen-burning shell – as suggested by current RGB nucleosynthesis models and observed Al overabundances – helium can be mixed into the stellar envelope. This in turn would increase the luminosity (and mass loss) along the RGB (Sweigart 1999) and thereby create less massive (i.e. bluer) HB stars with helium-enriched hydrogen envelopes. The helium enrichment increases the hydrogen burning rate, leading to higher luminosities (compared to canonical HB stars of the same temperature) and lower gravities. The gravities of stars hotter than about 20,000 K are not affected by this mixing process because these stars have only inert hydrogen shells.

Radiative levitation scenario: Grundahl et al. (1999) found a "jump" in the u, $u-y$ colour-magnitude diagrams of 15 globular clusters, which can be explained if radiative levitation of iron and other heavy elements takes place over the temperature range defined by the "low-gravity" BHB stars. This assumption has been confirmed in the case of M 13 by the recent high resolution spectroscopy of Behr et al. (1999). Grundahl et al. argue that super-solar abundances of heavy elements such as iron should lead to changes in model atmospheres which may be capable of explaining the disagreement between models and observations over the "critical" temperature range $11{,}500\ {\rm K} < T_{\rm eff} < 20{,}000$ K.

Send offprint requests to: S. Moehler

[⋆] Based on observations collected at the European Southern Observatory (ESO N$^{\underline{\rm o}}$ 60.E-145, 61.E-0145, 61.E-0361)

[⋆⋆] Hubble Fellow.

[⋆⋆⋆] Visiting Scientist, Universities Space Research Association.

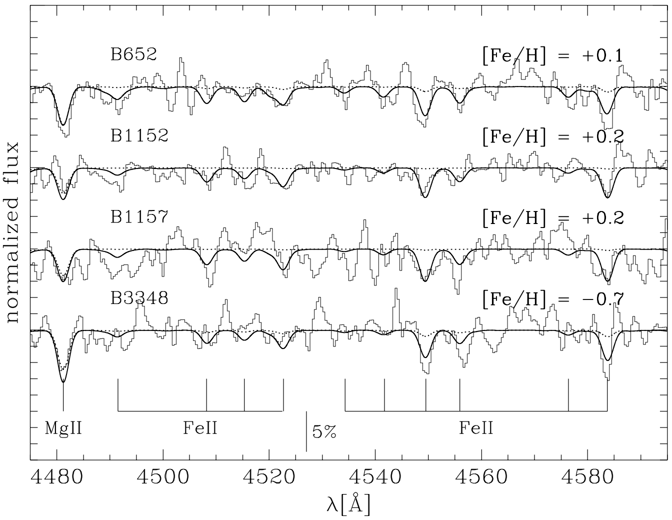

Fig. 1. The iron and magnesium lines as seen in the spectra of some of the stars in NGC 6752. The solid line marks a model spectrum for which we used a solar metallicity model stratification but adjusted all metals to [M/H] = -1.5 for the spectrum synthesis except iron. The iron abundance was then adjusted to the noted values to reproduce the marked Fe II lines. The dashed line marks a model spectrum for which we used the cluster metal abundance for all metals. Effective temperature and surface gravity for both models are those plotted in Fig. 2, upper and central panel, respectively. The temperatures of the stars range from 12,000 K (B3348) to 16,000 K (B1152). Obviously iron is strongly enriched whereas magnesium is consistent with the mean cluster abundance.

NGC 6752 is an ideal test case for these scenarios, since it is a very close globular cluster with a long blue HB extending to rather hot EHB stars. While previous data already cover the faint end of the EHB, we now obtained new spectra for 32 stars in and above the sparsely populated region between the BHB and the EHB stars. In this *Letter*, we present atmospheric parameters derived for a total of 42 BHB and EHB stars and discuss the constraints they may pose on the scenarios described above.

2. Observational data

We selected our targets from the photographic photometry of Buonanno et al. (1986) to cover the range 14.5$\leq V \leq$15.5. 19 stars were observed with the ESO 1.52m telescope (61.E-0145, July 22–25, 1998) and the Boller & Chivens spectrograph using CCD # 39 and grating # 33 (65 Å/mm). This combination covered the 3300 Å – 5300 Å region at a spectral resolution of 2.6 Å. The data reduction will be described in Moehler et al. (1999a). Prompted by the suggestion of Grundahl et al. (1999) that radiative levitation of heavy metals may enrich the atmospheres of BHB stars, we searched for metal absorption lines in these spectra. Indeed we found Fe II absorption lines in almost all spectra (for examples see Fig. 1).

13 stars were observed as backup targets at the NTT during observing runs dedicated to other programs (60.E-0145, 61.E-0361). The observations and their reduction are described in Moehler et al. (1999b). Those spectra have a spectral resolution of 5 Å covering 3350 to 5250 Å. No metal lines could be detected due to this rather low spectral resolution.

3. Atmospheric parameters

3.1. Fit procedure and model atmospheres

To derive effective temperatures, surface gravities and helium abundances we fitted the observed Balmer lines H_β to H_{10} (excluding H_ϵ because of possible blending problems with the Ca II H line) and the helium lines (He I 4026, 4388, 4471, 4922 Å) with stellar model atmospheres. We corrected the spectra for radial velocity shifts, derived from the positions of the Balmer and helium lines and normalized the spectra by eye.

We computed model atmospheres using ATLAS9 (Kurucz 1991) and used Lemke's version of the LINFOR[1] program (developed originally by Holweger, Steffen, and Steenbock at Kiel University) to compute a grid of theoretical spectra which include the Balmer lines H_α to H_{22} and He I lines. The grid covered the range 7,000 K $\leq T_{\rm eff} \leq$ 35,000 K, 2.5 $\leq \log g \leq$ 5.0, $-3.0 \leq \log \frac{n_{\rm He}}{n_{\rm H}} \leq -1.0$, at a metallicity of [M/H] = -1.5.

To establish the best fit we used the routines developed by Bergeron et al. (1992) and Saffer et al. (1994), which employ a χ^2 test. The fit program normalizes model spectra *and* observed spectra using the same points for the continuum definition. The results are plotted in Fig. 2 (upper panel). The errors are estimated to be about 10% in $T_{\rm eff}$ and 0.15 dex in $\log g$ (cf. Moehler et al. 1997). Representative error bars are shown in Fig. 2. To increase our data sample we reanalysed the NTT spectra described and analysed by Moehler et al. (1997). For a detailed comparison see Moehler et al. (1999a).

3.2. Iron abundances

Due to the spectral resolution and the weakness of the few observed lines a detailed abundance analysis (such as that of Behr et al., 1999) is beyond the scope of this paper. Nevertheless we can estimate the iron abundance in the stars by fitting the Fe II lines marked in Fig. 1. A first check indicated that the iron abundance was about solar whereas the magnesium abundance was close to the mean cluster abundance.

As iron is very important for the temperature stratification of stellar atmospheres we tried to take the increased iron abundance into account: We used ATLAS9 to calculate a solar metallicity atmosphere. The emergent spectrum was then computed from the solar metallicity model stratification by reducing the abundances of all metals M (except iron) to the cluster abundances ([M/H] = -1.5). It was not possible to compute an emergent spectrum that was fully consistent with this iron-enriched composition, since the ATLAS9 code requires a scaled solar composition. We next repeated the fit to derive $T_{\rm eff}$, $\log g$, and $\log \frac{n_{\rm He}}{n_{\rm H}}$ with these enriched model atmospheres. The results are plotted in Fig. 2 (central panel).

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[1] For a description see http://a400.sternwarte.uni-erlangen.de/∼ai26/linfit/linfor.html

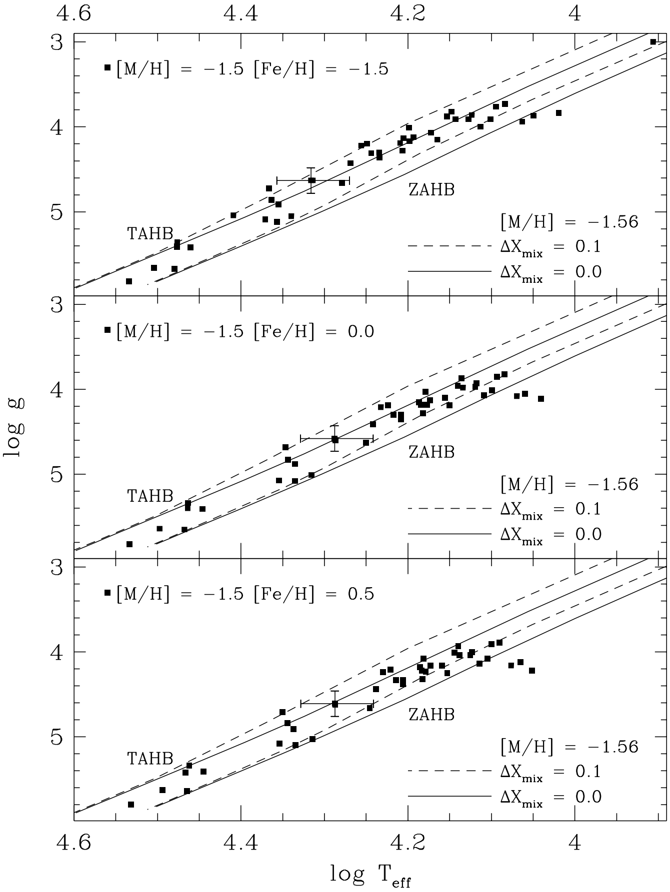

Fig. 2. Temperatures and gravities of the programme stars in NGC 6752. *upper panel*: determined from models with cluster metallicity ([M/H] = -1.5), *central panel*: adopting a solar metallicity model stratification ([M/H] = 0) and spectrum synthesis with solar iron abundance but cluster abundances for all other metals M ([M/H]=-1.5) *lower panel*: adopting a super–solar metallicity model stratification ([M/H] = $+0.5$) and iron abundance ([Fe/H] = $+0.5$) but cluster abundances ([M/H] = -1.5) for all other metals in the spectrum synthesis. For more details see text. Also plotted are the zero-age HB (ZAHB) and terminal-age HB (TAHB, i.e., central helium exhaustion) from the Sweigart (1999) tracks for metallicity [M/H] = -1.56. The dashed and solid lines correspond to tracks with and without mixing, respectively. $\Delta X_{\rm mix}$ measures the difference in hydrogen abundance X between the envelope ($X = X_{\rm env}$) and the innermost point reached by the mixing currents ($X = X_{\rm env} - \Delta X_{\rm mix}$) in the red giant precursors and is thus an indicator for the amount of helium mixed into the envelope of the red giant. Representative error bars are plotted

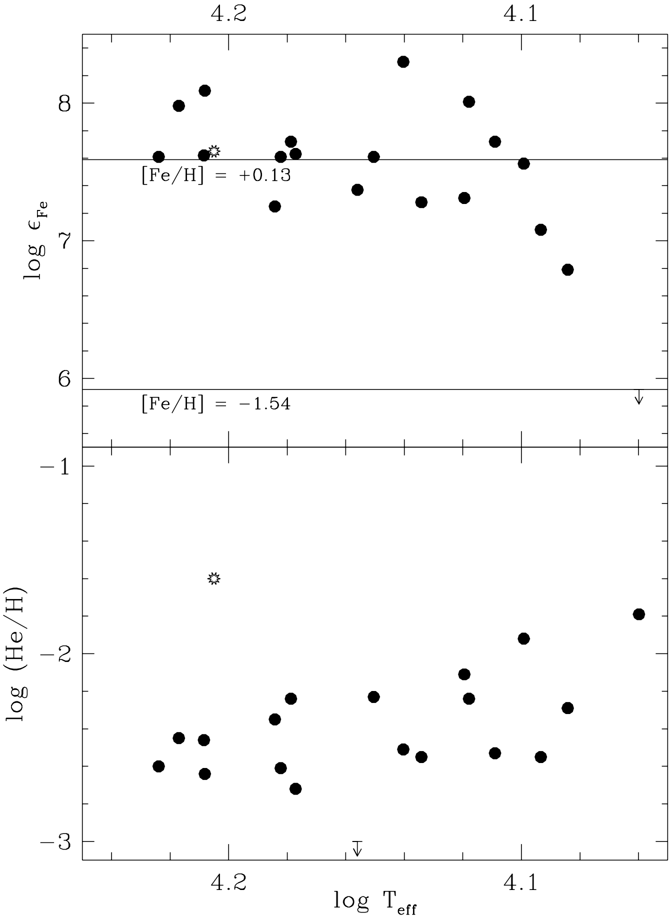

Fig. 3. The iron and helium abundances for the stars observed with ESO 1.52m telescope. Iron was not detected in the coolest star and is plotted as an upper limit. The trend to lower helium abundances for higher temperatures agrees with the findings of Behr et al. (1999). Iron is obviously enhanced to roughly solar abundances. The mean iron abundance as derived from our spectra ([Fe/H] = $+0.13$) and the cluster abundance ([Fe/H] = -1.54) are marked. The asterisk marks the results of Glaspey et al. (1989) for the hotter of their two BHB stars in NGC 6752

For each star observed at the ESO 1.52m telescope we then computed an "iron-enriched" model spectrum with $T_{\rm eff}$, $\log g$ as derived from the fits of the Balmer and helium lines with the "enriched" model atmospheres (cf. Fig. 2, central panel) and $\log \frac{n_{\rm He}}{n_{\rm H}} = -2$. The fit of the iron lines was started with a solar iron abundance and the iron abundance was varied until χ^2 achieved a minimum. As the radiative levitation in BHB stars is due to diffusion processes (which is also indicated by the helium deficiency found in these stars) the atmospheres have to be very stable. We therefore kept the microturbulent velocity ξ at $0\,{\rm km\,s^{-1}}$ – the iron abundances plotted in Fig. 3 are thus upper limits. The mean iron abundance turns out to be [Fe/H] $\approx +0.1$ dex (for 18 stars hotter than about 11,500 K) and ≤ -1.6 for the one star cooler than 11,500 K. Although the iron abundance for the hotter BHB stars is about a factor of 50 larger than the cluster abundance, it is smaller by a factor of 3 than the value of [Fe/H] = $+0.5$ estimated by Grundahl et al. (1999) as being necessary to explain the Strömgren u-jump observed in u, $u-y$ colour-magnitude diagrams.

Our results are in good agreement with the findings of Behr et al. (1999) for BHB stars in M 13 and Glaspey et al. (1989) for two BHB stars in NGC 6752. Again in agreement with Behr et al. (1999) we see a decrease in helium abundance with increasing temperature, whereas the iron abundance stays roughly constant over the observed temperature range.

3.3. *Influence of iron enrichment*

From Fig. 2 it is clear that the use of enriched model atmospheres moves most stars closer to the zero-age horizontal branch (ZAHB). The three stars between 10,000 K and 12,000 K, however, fall *below* the canonical ZAHB when fitted with enriched model atmospheres. This is plausible as the radiative levitation is supposed to start around 11,500 K (Grundahl et al. 1999) and the cooler stars therefore should have metal-poor atmospheres (see also Fig. 3 where the coolest analysed star shows no evidence of iron enrichment). We repeated the experiment by increasing the iron abundance to [Fe/H]=$+0.5$ (see Fig. 2 lower panel), which did not change the resulting values for $T_{\rm eff}$ and $\log\, g$ significantly.

Since HB stars at these temperatures spend most of their lifetime close to the ZAHB, one would expect the majority of the stars to scatter (within the observational error limits) around the ZAHB line in the $\log\, T_{\rm eff}$, $\log\, g$–diagram. However, this is not the case for the canonical ZAHB (solid lines in Fig. 2) even with the use of iron-enriched model atmospheres (central and lower panels in Fig. 2). The scatter instead seems more consistent with the ZAHB for moderate helium mixing (dashed lines in Fig. 2). Thus the physical parameters of HB stars hotter than $\approx 11{,}500$ K in NGC 6752, as derived in this paper, are best explained by a combination of helium mixing and radiative levitation effects.

4. Conclusions

Our conclusions can be summarized as follows:

1. We have obtained new optical spectra of 32 hot HB stars in NGC 6752 with 11,000 K $< T_{\rm eff} <$ 25,000. When these spectra (together with older spectra of hotter stars) are analysed using model atmospheres with the cluster metallicity ([Fe/H] = -1.5), they show the same "low-gravity" anomaly with respect to canonical HB models, that has been observed in several other clusters (Moehler 1999).
2. For 18 stars with $T_{\rm eff} >$ 11,500 K, we estimate a mean iron abundance of [Fe/H] $\approx +0.1$, whereas magnesium is consistent with the cluster metallicity. The hot HB stars in NGC 6752 thus show an abundance pattern similar to that observed in M 13 (Behr et al. 1999), which presumably arises from radiative levitation of iron (Grundahl et al. 1999).
3. When the hot HB stars are analysed using model atmospheres with an appropriately high iron abundance, the size of the gravity anomaly with respect to canonical HB models is significantly reduced. Whether the remaining differences between observations and canonical theory can be attributed to levitation effects on elements other than iron remains to be investigated by detailed modeling of the diffusion processes in the stellar atmospheres. With presently available models, the derived gravities for HB stars hotter than $\approx 11{,}500$ K are best fit by non-canonical HB models which include deep mixing of helium on the RGB (Sweigart 1999).

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