

# The peculiar properties of horizontal branch stars in $\omega$ Centauri <sup>1</sup>

C. Moni Bidin and S. Villanova

*Departamento de Astronomía, Universidad de Concepción, Casilla 160-C, Concepción, Chile;*

`cmbidin@astro-udec.cl`

G. Piotto

*Dipartimento di Astronomia, Università di Padova, Vicolo dell'Osservatorio 3, I-35122 Padua, Italy*

and

S. Moehler

*European Southern Observatory, Karl-Schwarzschild-Str. 2, 85784 Garching, Germany*

and

F. D'Antona

*INAF, Osservatorio Astronomico di Roma, Via Frascati 33, 00040 Monteporzio Catone, Roma, Italy*

## ABSTRACT

We measured temperatures, gravities, and masses for a large sample of blue horizontal branch stars in  $\omega$  Centauri, comparing the results with theoretical expectations for canonical and He-enriched stars, and with previous measurements in three other clusters. The measured gravities of  $\omega$  Cen stars are systematically lower than canonical models, in agreement with expectations for He-enriched stars, and contrary to that observed in the comparison clusters. However, the derived masses are unrealistically too low as well. This cannot be explained by low gravities alone, nor by any of the other parameters entering in the calculation. We find that the same stars are not brighter than their analogs in the other clusters, contrary to the expectations of the He-enrichment scenario. The interpretation of the results is thus not straightforward, but they reveal an intrinsic, physical difference between HB stars in  $\omega$  Cen and in the three comparison clusters.

*Subject headings:* Stars: horizontal-branch — Globular clusters: individual (NGC 5139)  
— Stars: evolution — Stars: atmospheres — Stars: fundamental parameters

## 1. INTRODUCTION

The nature of the second parameter, aside from metallicity, which determines the morphology of the horizontal branch (HB) in globular clusters (GCs), is one of the most long-standing problems of modern astrophysics. In fact, a lower metallicity favors the formation of hotter and bluer HB stars, but clusters with the same metallicity can show very different HB morphology (Sandage & Wildey 1967), and an HB extended far toward the blue is observed even in some metal-rich GCs (e.g., Rich et al. 1997). The helium abundance has been early proposed, among others, as this second parameter (Sweigart 1997; D’Antona et al. 2002; see Catelan 2009, for a review) because, during the He-burning phase, helium-rich stars are expected to be hotter than objects of canonical composition. This model has recently drawn much attention, triggered by the discovery of multiple stellar populations in GCs (Piotto et al. 2005, 2007). In fact, Piotto et al. (2005) showed that a different metallicity is not the cause of the main-sequence split observed in  $\omega$  Centauri (Bedin et al. 2004), and the only explanation is that the bluer sequence is greatly enriched in helium, about 50% more He-rich ( $Y=0.38$ ) than in normal metal-poor GC stars (Norris 2004; Piotto et al. 2005). In this scenario, the blue HB stars observed in many GCs could be the progeny of the He-enriched second stellar generation. Unfortunately, diffusion processes completely alter the surface chemical abundances of hot HB stars (e.g., Behr et al. 1999), preventing a direct demonstration of the connection between multiple populations and HB morphology. Nevertheless, an increased helium content can be indirectly deduced from other observable quantities, because He-enriched HB stars are predicted to be brighter (Sweigart 1987) and to occupy different loci in the temperature–gravity plane (Moehler et al. 2003).

In this Letter, we present the results of our investigation aimed to search for an indirect indication of helium enrichment among blue HB stars in  $\omega$  Centauri, to test the He-enrichment scenario and its predicted effects on the HB morphology. This cluster is the ideal target for our purpose, because it hosts a very complex stellar population, comprising three known MSs and six sub-giant branches (Bellini et al. 2010).

---

<sup>1</sup>Based on observations with the ESO Very Large Telescope at Paranal Observatory, Chile (proposal ID 076.D-0810)

## 2. OBSERVATIONS AND DATA ANALYSIS

We selected 116 target stars from the ground-based photometry of Bellini et al. (2009). They span a wide portion of the cluster HB, from the blue edge of the RR Lyrae gap to the Blue Hook objects ( $T_{\text{eff}} \geq 33\,000$  K) 5 mag fainter. In this Letter, we will focus on the comparison of  $\omega$  Cen stars with other clusters and theoretical models. We therefore limit the analysis to  $T_{\text{eff}} \leq 33\,000$  K, because hotter Blue Hook stars are not included in the canonical models and are not present in the comparison clusters. A full analysis of the results, including the Blue Hook, will be presented in a forthcoming paper.

The data were collected at Paranal Observatory in service mode between 2006 January and April, with FORS2@UT1 in MXU mode. The selected 600B grism, coupled with 0'5-wide slits, gave spectra of resolution  $R \approx 1600$  from the atmospheric cutoff to approximately 5900 Å. Three 45 minute spectra for faint stars and two 45 minute spectra for bright ones were acquired. Data were reduced with the FORS pipeline<sup>2</sup>, and the spectra were extracted under IRAF<sup>3</sup>, subtracting the nearby sky spectrum within the same slit. Finally, the spectrum of the standard star LTT4816 (Hamuy et al. 1992), secured during observations, was used to flux-calibrate the object spectra, whose resulting signal-to-noise ratio was between 50 and 150. Heliocentric radial velocities (RV) were measured with the IRAF *fxcor* task, cross-correlating (Tonry & Davis 1979) the spectra with synthetic templates of adequate parameters as estimated from the stellar position in the color-magnitude diagram (CMD). Considering the internal velocity dispersion of the cluster ( $\sim 13$  km s<sup>-1</sup>, Sollima et al. 2005) and the errors of measurements (about 30 km s<sup>-1</sup>), the RV of all the observed stars is consistent with cluster membership.

The atmospheric parameters of target stars were measured fitting the observed Balmer and helium lines with stellar model atmospheres, computed with ATLAS9 (Kurucz 1993). We used Lemke's version<sup>4</sup> of the LINFOR program (developed originally by Holweger, Steffen, and Steenbock at Kiel University) to compute a grid of synthetic spectra. Stars showing iron lines in the 4450–4600 Å region, indicating active atmospheric diffusion (Moehler et al. 1999), or being hotter than 13 000 K (as deduced from the position in the CMD), were fitted with metal-rich models ( $[M/H]=+0.5$ ) with varying surface helium abundance, to account

---

<sup>2</sup>[www.eso.org/sci/data-processing/software/pipelines/index.html](http://www.eso.org/sci/data-processing/software/pipelines/index.html)

<sup>3</sup>IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

<sup>4</sup>For a description see <http://a400.sternwarte.uni-erlangen.de/~ai26/linfit/linfor.html>

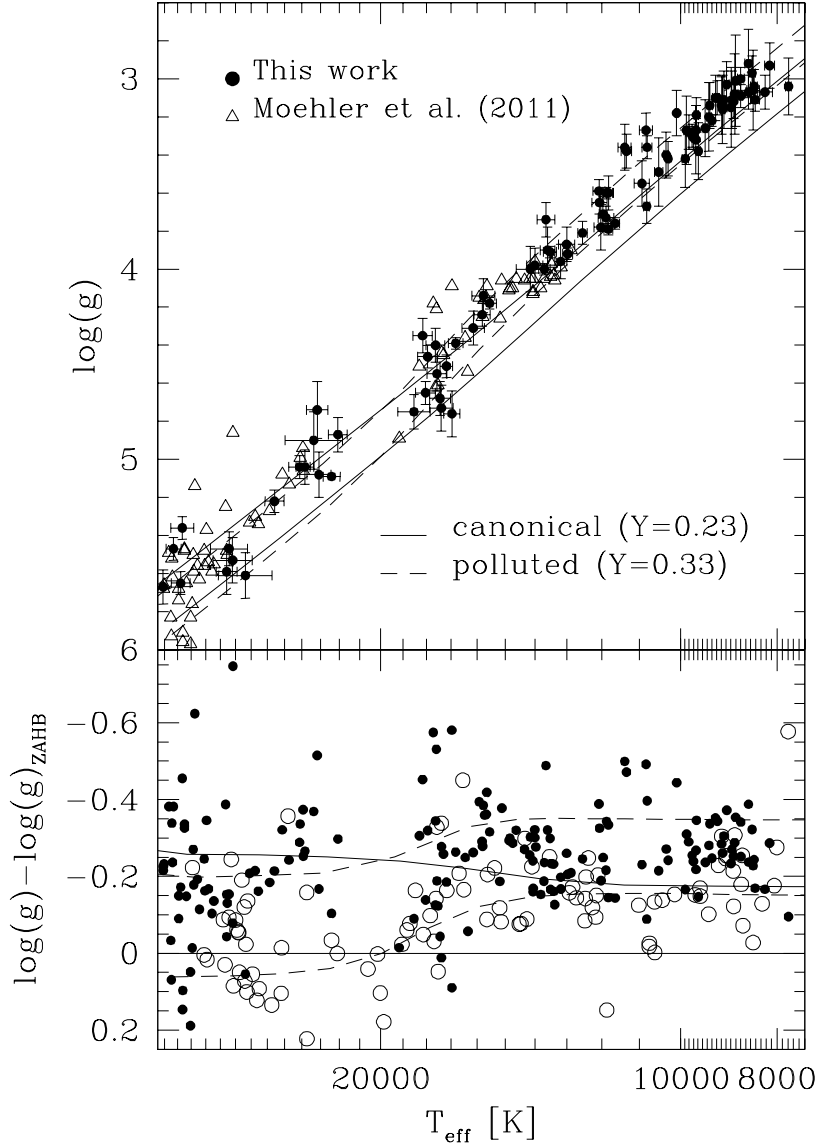


Fig. 1.— *Upper panel:* distribution of  $\omega$  Cen stars in the temperature-gravity plane. The Zero-Age and Terminal-Age HB (ZAHB and TAHB, respectively), for both canonical and He-enriched models are also indicated. *Lower panel:* comparison of stars in  $\omega$  Cen (full dots) and members of three other clusters (open circles). The vertical coordinate is the difference between the stellar gravity and the corresponding value of the canonical ZAHB at the same temperature. The plot is thus analogous to the  $T_{\text{eff}}-\log(g)$  space of the upper panel, but the horizontal axis coincides with the canonical ZAHB.

for the effects of radiative levitation of heavy elements (e.g., Moehler et al. 2000). This was done even for five stars hotter than 11 500 K not satisfying these criteria, because the observed helium lines were clearly too weak compared to the fitted models when diffusion was not taken into account. The cooler stars were fitted with cluster-metallicity models ( $[M/H]=-1.5$ ) with helium abundance fixed at the solar value, because their He lines are very weak and not observed at our resolution. In a few cases of doubt about the correct model to use, we adopted the set of model spectra that returned the lower  $\chi^2$  of the fit. The best fit to the observed spectra was obtained by means of 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 spectral lines used in the procedure included the Balmer series from  $H_\beta$  to  $H_{12}$ , except for  $H_\epsilon$  to avoid the blended Ca II H line, four He I lines (4026 Å, 4388 Å, 4471 Å, and 4921 Å) for stars whose helium abundance was not kept fixed, and the He II lines 4542 Å and 4686 Å when visible in the spectra of the hottest stars. The routines estimate the errors on the derived parameters from the  $\chi^2$  of the fit (see Moehler et al. 1999), but neglect all other sources of errors (e.g., defects in normalization, flat-field correction, sky subtraction). We therefore obtained a better estimate of the true errors multiplying the output values by 3 (R. Napiwotzki, private communication).

Stellar masses were calculated from the measured temperatures and gravities, through the relation:

$$\log \frac{M}{M_\odot} = \log \frac{g}{g_\odot} - 4 \cdot \log \frac{T}{T_\odot} + \log \frac{L}{L_\odot}, \quad (1)$$

where

$$\log \frac{L}{L_\odot} = -0.4 \cdot (V - (m - M)_0 - 3.1 \cdot E(B - V) + BC - 4.74). \quad (2)$$

We assumed  $T_\odot=5777$  K,  $\log g_\odot=4.44$ ,  $(m-M)_0=13.75\pm 0.13$  (van de Ven et al. 2006), and  $E(B - V)=0.12\pm 0.01$  (Harris 1996, 2010 December Web version). The bolometric correction (BC) was derived from effective temperatures through the empirical calibration of Flower (1996). Errors on masses were derived from propagation of errors.

### 3. RESULTS

Our results are plotted in the upper panel of Figure 1, where we show the position of the program stars in the temperature-gravity space, superimposed to the theoretical zero-age and terminal-age HB (ZAHB and TAHB, respectively) from Moehler et al. (2003), for canonical ( $Y=0.23$ ) and He-enriched ( $Y=0.33$ ) models. In the same figure we include 78 stars from Moehler et al. (2011), who measured the atmospheric parameters with the same procedure as in the present work, but based on medium-resolution FLAMES spectra, and

a different set of model spectra for stars above 20 000 K. The two sets of data behave very similarly in the  $T_{\text{eff}}\text{-}\log(g)$  plane. The comparison of the eight stars in common confirms the good agreement between the two works: the mean difference in gravity is null ( $\leq 0.01$  dex), while the difference in temperature is small (155 K), and becomes negligible (25 K) after the exclusion of two stars with very large errors ( $\geq 1500$  K). Our mass estimates are on average higher by  $0.035 M_{\odot}$ , an offset accounted for by the fainter magnitudes (0.09 mag the mean difference) from the Castellani et al. (2007) catalog used by Moehler et al. Given the excellent agreement, we will merge the two datasets together.

The surface gravity of stars cooler than  $\sim 18\,000$  K is systematically lower by about 0.2–0.3 dex with respect to canonical models, while they closely follow the trend of He-enhanced models at all temperatures. In the lower panel of Figure 1 we compare these results with similar measurements obtained in three GCs, namely NGC 6752 (Moni Bidin et al. 2007), M80 and NGC 5986 (Moni Bidin et al. 2009). We adopt as vertical coordinate the difference between the measured  $\log(g)$  and the value of the canonical ZAHB at the corresponding temperature. The comparison reveals that the HB stars in  $\omega$  Cen and in the other GCs behave very differently. We note that the stars of the comparison clusters do not completely agree with canonical models, whose expectation is to find the majority of the objects next to the ZAHB, and not to the TAHB as observed. Even so,  $\omega$  Cen stars clearly show lower gravities – at a given effective temperature – with respect to stars in other GCs. Observational errors tend to mask the general trend, but there is an offset of 0.15 dex at the cooler end, which decreases at higher temperatures and fades out around 18 000 K, to reappear even larger ( $\geq 0.2$  dex) among hot stars at 25 000–28 000 K. However, we find a problem in the estimate of stellar masses, summarized in the upper panel of Figure 2: while the results in the comparison clusters roughly agree with expectations (see Moni Bidin et al. 2007, 2009, for a complete discussion), the masses of  $\omega$  Cen stars are constantly underestimated at all temperatures. Interestingly enough, Moehler & Sweigart (2006) found very similar results for HB stars in NGC 6388. This is a very peculiar cluster, as it has an extended, blue HB (Rich et al. 1997) despite its high metallicity ( $[\text{Fe}/\text{H}]=-0.6$ ). This has been interpreted in terms of an extreme He-enrichment (up to  $Y=0.40$ , Caloi & D’Antona 2007), as in the case of its twin cluster, NGC 6441. While Moehler & Sweigart (2006) cast doubts on their results due to the large uncertainties caused by stellar crowding in this compact, bulge cluster, these results are very similar to what we find now in  $\omega$  Cen.

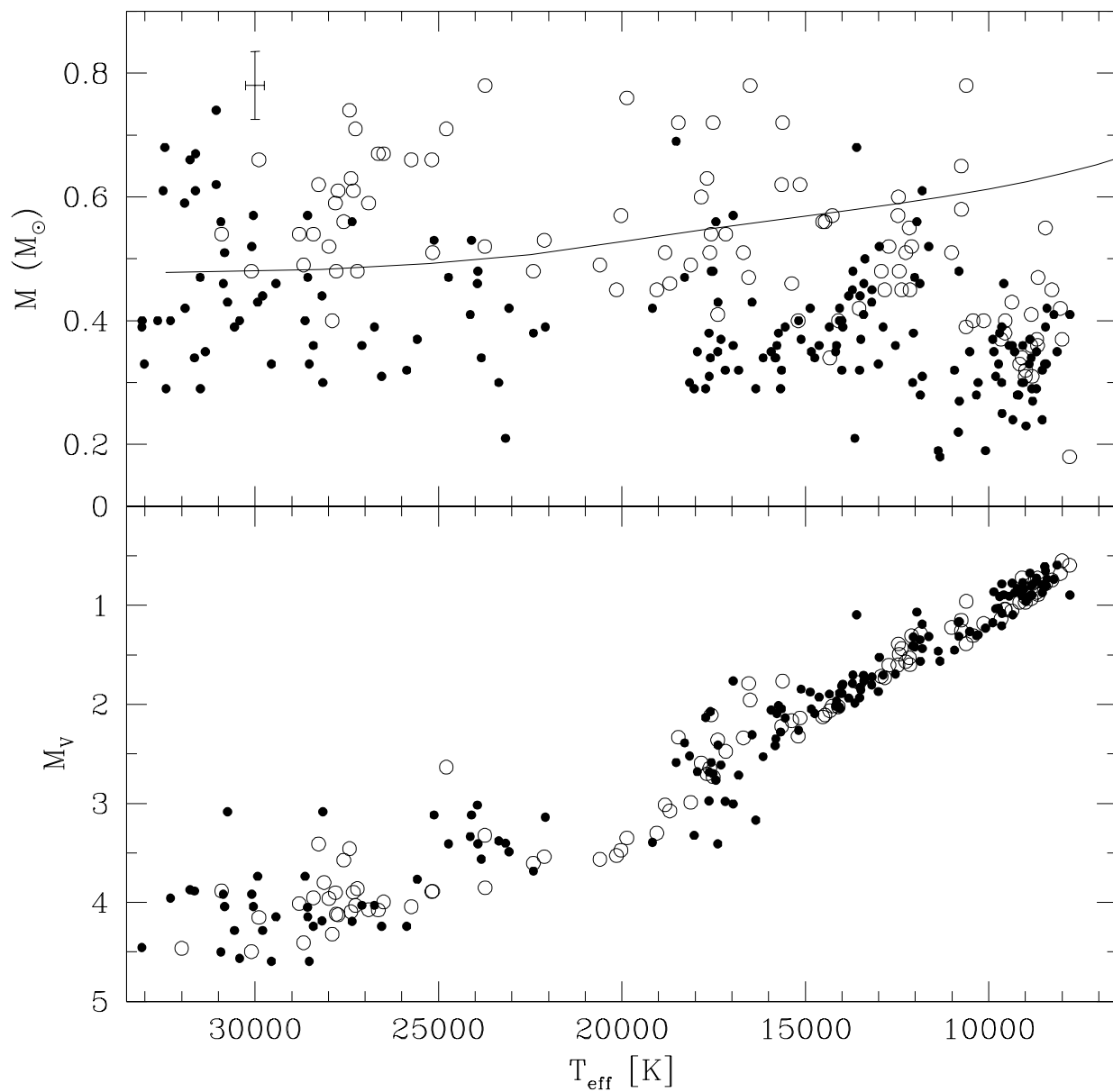


Fig. 2.— *Upper panel:* stellar masses, calculated through Equation (1). The line indicates the canonical model expectation. *Lower panel:* absolute magnitudes, estimated from distance moduli and reddening given in Section 2 and Moni Bidin et al. (2007, 2009). Different symbols are used for  $\omega$  Cen and other cluster stars, as in the lower panel of Figure 1.

#### 4. DISCUSSION

In the temperature-gravity plane, the  $\omega$  Cen HB stars match the expectations of He-enriched models rather than canonical ones. However, the resulting underestimate of their mass prevents us from straightforwardly concluding that this is evidence of helium enrichment. In fact, the progenies of He-rich stars in the HB phase should not be noticeably less massive than stars of canonical composition (D’Antona & Caloi 2004), and the difference at any temperature is expected to be tiny ( $\leq 0.03 M_{\odot}$ , Moehler et al. 2003). Moreover, the derived masses are on average well below the value required to ignite helium in the core ( $\sim 0.45 M_{\odot}$ ).

The easiest interpretation of our observations is the presence of a systematic error, biasing the results toward lower gravities and, as a consequence, lower masses. However, in this work we used the same instrument, software, and models as Moni Bidin et al. (2007, 2009), finding a clear difference between  $\omega$  Cen and the other clusters, while our measurements well agree with Moehler et al. (2011), who also investigated  $\omega$  Cen but with a different instrument, higher resolution, different models for stars hotter than 20 000 K, and only a subset of Balmer lines. Therefore, even if we cannot completely exclude an observational bias with respect to theoretical expectations, the difference between  $\omega$  Cen and the three comparison clusters must be real: *HB stars in  $\omega$  Cen are intrinsically different to their analogs in other GCs.* The same conclusion can be drawn even if the offset is a product of the inadequacy of the employed models: in this case, they would be reproducing sufficiently well the atmospheric structure of the HB objects in the comparison clusters, but not in  $\omega$  Cen, hence a physical difference would be present.

The observed trends cannot be due to a wrong (hotter) temperature scale. In fact, for each star we translated the measured temperature in a reddening estimate, comparing the observed ( $B - V$ ) color to the theoretical value obtained interpolating the Kurucz (1993) grid, for the same metallicities as the model spectra used in the fits. The average value is  $E(B - V) = 0.114$ , in perfect agreement with the literature, and with no significant trend along the HB. A temperature scale hotter by 10% (5%) would have caused an overestimate of reddening by 0.04 (0.02) mag at 10 000 K. In Figure 3 we compare the  $H_{\beta}$  line profiles of two stars with similar temperature in M 80 and  $\omega$  Cen: the line core and depth are very similar, indicating no noticeable difference in temperature, but the star in M 80, whose measured gravity is 0.40 dex higher, shows wider wings. This comparison indicates that the peculiar stellar gravities reflect a real difference in the spectra of the target stars. We are aware that some stellar parameters unaccounted for in our study, such as stellar wind and rotation, can cause wider line wings mimicking a difference in gravity, and this degeneracy cannot be avoided at our resolution. The underestimate of gravities can also be caused by



the stratification of elemental abundances due to diffusion processes (LeBlanc et al. 2010). However, a systematic difference in one of these parameters, affecting  $\omega$  Cen but not the other clusters, would be even more puzzling, and it is harder to postulate at this stage. It must also be noted that the mass underestimate does not completely follow the trend of the difference in gravity: while this seems to vary with temperature as noted before, the masses in  $\omega$  Cen are constantly underestimated by  $\sim 0.15 M_{\odot}$  for  $T_{\text{eff}} \geq 10\,000$  K. For example, at  $T_{\text{eff}} \sim 16\,000$ - $18\,000$  K there is a clear offset in masses, but not in gravities. This indicates that low gravities may play a role, but at least another effect should be at work, causing the observed mass underestimate.

All the comparison clusters have similar metallicity ( $[\text{Fe}/\text{H}] \approx -1.5$  Harris 1996), while  $\omega$  Cen shows a large spread up to  $[\text{Fe}/\text{H}] = -0.6$  (e.g., Sollima et al. 2005). Nevertheless, it is unlikely that the higher metallicity is the origin of the peculiar results in  $\omega$  Cen: the largest differences are found for stars hotter than  $\sim 11\,500$  K, whose surface abundances are altered by diffusion processes. Behr (2003) and Pace et al. (2006) showed that, in the presence of diffusion, the surface abundance patterns are very similar in clusters of very different initial metallicity. The stars in all the clusters should therefore show the same behavior independently of their primordial metal content, especially at  $15\,000$ - $16\,000$  K where diffusion reaches its maximum strength (Moni Bidin et al. 2009). Moreover, Moehler et al. (2000) found no peculiarity in the measured gravity and mass of two stars in 47 Tuc ( $[\text{Fe}/\text{H}] = -0.7$ ), although using low-metallicity models. We repeated the measurements assuming different values of the model metallicity, to test how this parameter can affect the results. We found small differences in the stellar parameters, but the general behavior was unaltered: a higher model metallicity indeed returned slightly higher gravities, but higher temperatures too. As a consequence, the points were shifted almost parallel to the theoretical tracks in the  $T_{\text{eff}}$ - $\log(g)$  plane, while the masses were increased by less than  $0.05 M_{\odot}$ .

The blanketing effect should be lower in metal-poor stars than in the solar-metallicity stars used to calibrate the adopted  $T_{\text{eff}}$ -BC relation, and this could cause the underestimate of the BC and of the mass. The adopted BC should be a good approximation for the stars hotter than the Grundahl jump (Grundahl et al. 1999), because radiative levitation increases their surface abundances to super-solar values. As already noted, the effect should be independent of their primordial metallicity, thus the BC does not explain the offset of  $\omega$  Cen with respect to the other GCs. At cooler temperatures, the offset could be explained by the BC if  $\omega$  Cen stars were more metal-poor than in the other GCs, thus decreasing their BC by  $\sim 0.4$  mag. Indeed,  $\omega$  Cen hosts a metal-poor sub-population at  $[\text{Fe}/\text{H}] = -2$  (e.g., Pancino et al. 2011), but the BC varies by less than  $0.15$  mag for stars at  $8\,000$ - $10\,000$  K in the whole range between solar metallicity and  $[\text{Fe}/\text{H}] = -2$  (Cassisi et al. 1999; Alonso et al. 1999). A wrong distance modulus or reddening could also cause wrong mass estimates, but the required correction

to increase the masses by  $0.1 M_{\odot}$  is huge ( $\geq 0.4$  mag in distance modulus,  $\geq 0.13$  mag in reddening). The recent literature estimates agree on these quantities within 0.1 and 0.01 mag, respectively, allowing only negligible variations of the mass estimates. Even an offset in the photometric zero-point could cause the observed offset, but comparing the  $V$  mag of Bellini et al. (2009) with the values of Castellani et al. (2007) and Momany et al. (2004) we found only a small difference ( $\leq 0.1$  mag) in the direction opposite to that required, with the magnitudes used here being brighter than in the other catalogs. In conclusion, none of the photometric parameters (stellar magnitude, BC, distance modulus, and reddening) entering in the calculation of the stellar mass through Equation (2) offers a viable explanation of our results.

He-enriched HB stars are expected to be brighter than analogous objects of canonical composition (e.g., Caloi & D’Antona 2007; Catelan et al. 2009), and the increased luminosity should balance the lower gravities in Equation (1), returning a similar mass. All other parameters being the same,  $M_V$  should be brighter by 0.25-0.38 mag to compensate a decrease of 0.10-0.15 dex in gravity. On the contrary, in the lower panel of Figure 2 the perfect match between the absolute magnitudes of the HB of  $\omega$  Cen and the other clusters is clear. The too low values obtained for the stellar masses could therefore also be interpreted as due to the lack of increased flux, instead of too low gravity estimates. It could be argued that He-enriched stars could not necessarily be brighter in the  $V$  band, because the bolometric luminosity is the quantity entering in Equation (1). Thus, the detailed spectral energy distribution (SED) of He-enriched and canonical stars is required to properly deduce their luminosity from the  $V$  magnitude through Equation (2). However, great differences are not expected for stars hotter than 12 000 K, because the diffusion processes decrease the atmospheric He-abundance well below solar values in both cases. In fact, we find no difference in surface helium abundance between  $\omega$  Cen and the other clusters, and  $\log(N_{He}/N_H) \leq -1.5$  for all the stars. With atmospheres of very similar chemical composition, their SED should not be very different, and even the known UV-enhanced flux of these stars (Grundahl et al. 1999) should have the same effects irrespective of the primordial helium content.

## 5. CONCLUSIONS

Blue HB stars in  $\omega$  Cen show lower gravities with respect to both canonical models and analogous stars in other GCs, but their stellar masses are underestimated, and their visual absolute magnitudes are very similar to those of the comparison clusters. Neither the low gravities nor the other parameters involved in the calculation can explain the too low masses. We can firmly conclude that these results reveal an intrinsic difference between the blue HB

stars in  $\omega$  Cen and their analogs in other GCs, but its interpretation is not straightforward. The lower gravities follow the expectations for He-rich stars, but the magnitudes and masses do not.

C.M.B. acknowledges support from the Chilean projects *Centro de Astrofísica* FON-DAP No. 15010003 and the Chilean Centro de Excelencia en Astrofísica y Tecnologías Afines (CATA) BASAL PFB/06. G.P. acknowledges support by MIUR under the program PRIN2007 (prot. 20075TP5K9), and PRIN-INAF 2009. The authors are grateful to the anonymous referee for his/her fruitful report.

## REFERENCES

- Alonso, A., Arribas, S., & Martínez-Roger, C. 1999, *A&AS*, 140, 261
- Bedin, L. R., Piotto, G., Anderson, J., Cassisi, S., King, I. R., Momany, Y., & Carraro, G. 2004, *ApJ*, 605, L125
- Behr, B. B., Cohen, J. G., McCarthy, J. K., & Djorgovski, S. G. 1999, *ApJ*, 517, L135
- Behr, B. B. 2003, *ApJS*, 149, 67
- Bellini, A., et al. 2009, *A&A*, 493, 959
- Bellini, A., Bedin, L. R., Piotto, G., Milone, A. P., Marino, A. F., & Villanova, S. 2010, *AJ*, 140, 631
- Bergeron, P., Saffer, R. A., & Liebert, J. 1992, *ApJ*, 394, 228
- Caloi, V., & D’Antona, F. 2007, *A&A*, 463, 949
- Cassisi, S., Castellani, V., degl’Innocenti, S., Salaris, M., & Weiss, A. 1999, *A&AS*, 134, 103
- Castellani, V., et al. 2007, *ApJ*, 663, 1021
- Catelan, M., Grundahl, F., Sweigart, A. V., Valcarce, A. A. R., & Cortés, C. 2009, *ApJ*, 695, L97
- Catelan, C. 2009, *Ap&SS*, 320, 261
- D’Antona, F., Caloi, V., Montalbán, J., Ventura, P., & Gratton, R. 2002, *A&A*, 395, 69
- D’Antona, F., & Caloi, V. 2004, *ApJ*, 611, 871

- Flower, P. J. 1996, *ApJ*, 469, 355
- Grundahl, F., Catelan, M., Landsman, W. B., Stetson, P. B., & Andersen, M. I. 1999, *ApJ*, 524, 242
- Hamuy, M., Walker, A. R., Suntzeff, N. B., Gigoux, P., Heathcote, S. R., & Phillips, M. M. 1992, *PASP*, 104, 533
- Harris, W. E. 1996, *AJ*, 112, 1487
- Kurucz, R. 1993, *ATLAS9 Stellar Atmosphere Programs and 2 km/s grid*. Kurucz CD-ROM No. 13. Cambridge, Mass.: Smithsonian Astrophysical Observatory, 1993., 13
- LeBlanc, F., Hui-Bon-Hoa, A., & Khalack, V. R. 2010, *MNRAS*, 409, 1606
- Moehler, S., Dreizler, S., Lanz, T., Bono, G., Sweigart, A. V., Calamida, A., & Nonino, M. 2011, *A&A*, 526, 136
- Moehler, S., Landsman, W. B., & Dorman, B. 2000, *A&A*, 361, 937
- Moehler, S., Landsman, W. B., Sweigart, A. V., & Grundahl, F. 2003, *A&A*, 405, 135
- Moehler, S., Sweigart, A. V., & Catelan, M. 1999, *A&A*, 351, 519
- Moehler, S., Sweigart, A. V., Landsman, W. B., & Heber, U. 2000, *A&A*, 360, 120
- Moehler, S., & Sweigart, A. V. 2006, *A&A*, 455, 943
- Momany, Y., Bedin, L. R., Cassisi, S., Piotto, G., Ortolani, S., Recio-Blanco, A., De Angeli, F., & Castelli, F. 2004, *A&A*, 420, 605
- Moni Bidin, C., Moehler, S., Piotto, G., Momany, Y., & Recio-Blanco, A. 2007, *A&A*, 474, 505
- Moni Bidin, C., Moehler, S., Piotto, G., Momany, Y., & Recio-Blanco, A. 2009, *A&A*, 498, 737
- Napiwotzki, R., Green, P. J., & Saffer, R. A. 1999, *ApJ*, 517, 399
- Norris, J. 2004, *ApJ*, 612, L25
- Pace, G., Recio-Blanco, A., Piotto, G., & Momany, Y. 2006, *A&A*, 452, 493
- Pancino, E., Mucciarelli, A., Sbordone, L., Bellazzini, M., Pasquini, L., Monaco, L., & Ferraro, F. R. 2011, *A&A*, 527, A18

- Piotto, G., et al. 2005, *ApJ*, 621, 777
- Piotto, G., et al. 2007, *ApJ*, 661, L53
- Rich, R. M., et al. 1997, *ApJ*, 484, L25
- Saffer, R. A., Bergeron, P., Koester, D., & Liebert, J. 1994, *ApJ*, 432, 351
- Sandage, A. & Wildey, R. 1967, *ApJ*, 150, 469
- Sollima, A., Pancino, E., Ferraro, F. R., Bellazzini, M., Straniero, O., & Pasquini, L. 2005, *ApJ*, 634, 332
- Sweigart, A. V. 1987, *ApJS*, 65, 95
- Sweigart, A. V. 1997, *ApJ*, 474, L23
- Tonry, J. & Davis, M. 1979, *AJ*, 84, 1511
- van de Ven, G., van den Bosch, R. C. E., Verolme, E. K., & de Zeeuw, P. T. 2006, *A&A*, 445, 513

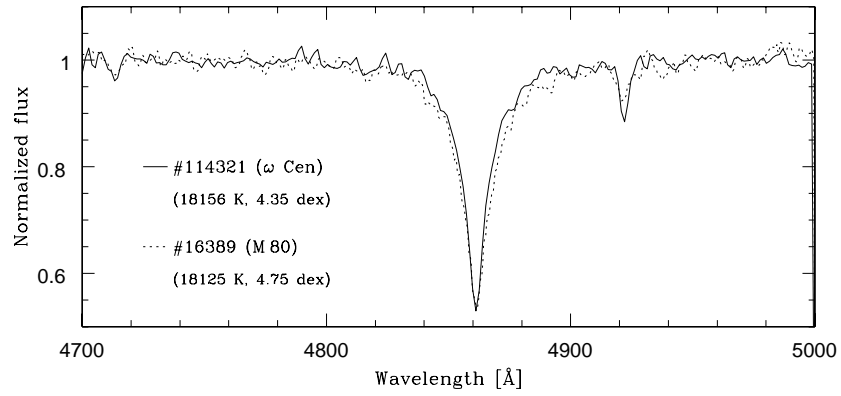


Fig. 3.— Comparison of the  $H_{\beta}$  lines of one of our program star (full line) and a HB star in M 80 at the same temperature. Derived temperatures and gravities are given.