On the Blue Tail of Horizontal Branch Stars

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Abstract. We discuss theoretical predictions for ZAHB models constructed either by including or neglecting the He extra-mixing effect recently suggested by Sweigart (1997). The comparison in the log\(T_e\) − log\(g\) plane suggests that within current observational uncertainties canonical hot HB models based on new input physics agree with empirical data in Galactic globular clusters and in the field. We also briefly discuss the impact of the new class of variable stars EC14026 on constraining the parameters of blue HB stars and their distribution along the tail.

1. Introduction

Only with a naïve approach to stellar astrophysics one could not realize that Horizontal Branch (HB) stars are the crossroad of several astrophysical problems concerning the evolutionary properties and the final fate of low-mass stars as well as a fundamental laboratory for estimating important astrophysical parameters such as primordial He content by means of the \(R\) parameter, stellar distances via RR Lyrae luminosity and ages of Globular Clusters (GCs) by means of the \(\Delta V\) method (see for a comprehensive review Castellani 1999). Moreover, blue HB stars are currently adopted for tracing the luminous mass distribution of the Galactic halo, and in turn for constraining the primordial structure of the Galaxy (Kinman et al. 1996; Sluis & Arnold 1998).

The physical mechanisms governing core He burning evolutionary phases in low-mass stars were established in the seventies by Castellani et al. (1969), Iben & Rood (1970), and by Sweigart & Gross (1978). After these pioneering papers the evolutionary scenario has been soundly supplemented by several thorough investigations aimed at improving the input physics such as radiative opacities, equation of state and nuclear reaction rates (Dorman et al. 1993; Castellani et al. 1991; Cassisi et al. 1998). Thanks to large grids of HB models it has also been possible to account for the dependence of HB and post-HB evolutionary phases on chemical composition and therefore to develop a homogeneous theoretical

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framework for He burning phases (Dorman et al. 1993; Cassisi et al. 1998). During the last few years the HB scenario has undergone some sudden jerks due to new observational and theoretical results.

- New HST photometric data collected by Rich et al. (1997) disclosed an interesting feature of blue HB stars in Galactic GCs. Thanks to the accuracy of these data they suggested that the luminosity of HB stars in NGC6388 and NGC6441 is tilted, i.e. when moving from low to high temperature the HB luminosity undergoes an increase of the order of $\Delta V = 0.5$ mag. This observational evidence was independently supported by Grundahl et al. (1998) who found a similar feature in M13 HB stars by adopting Strömgren photometric data.

- Further observational evidence recently brought out is the occurrence of hot HB stars in some metal-rich GCs such as 47 Tuc and NGC362 (O'Connell et al. 1997; Dorman et al. 1997). This feature is at odds with predictions provided by canonical HB models, since it has been generally assumed so far that the blue tail is the fingerprint of metal-poor clusters.

- New photometric data also suggest that the gaps which appear along the blue tail of some GCs such as NGC2808, M80 and M13 are real (Sosin et al. 1997; Ferraro et al. 1998), thus confirming the results obtained by Newell (1973) for hot HB stars in the field. This evidence has been soundly supplemented by the recent discovery of a new class of variable stars called EC14026 by Kilkenny et al. (1997), which are characterized by surface gravities and effective temperatures typical of Extreme HB (EHB) stars.

The new data stimulated several theoretical investigations which accounted for new physical mechanisms in explaining the HB morphology and the evolutionary properties of EHB stars. In particular, Sweigart (1997, 1998) suggested that the chemical anomalies observed in globular cluster red giants can be due to an extra-mixing which takes place inside their envelope. If this mechanism, which could be caused by internal rotation, is actually at work in real stars, the He abundance in the stellar envelope should also be enhanced. The increase in the He content brings about that these noncanonical HB models are, at fixed stellar mass, both brighter and bluer than the canonical ones. This effect is not constant along the HB since fast rotators undergo larger He enhancement than slow rotators. This gradient would imply that red HB stars are marginally affected by this phenomenon (slow rotators), whereas blue HB stars are strongly affected by extra-mixing (fast rotators). The main outcomes of this scenario have been exhaustively investigated by Sweigart (1998) and can be summarized as follows: 1) the extra-mixing hypothesis accounts for tilted HB morphology; 2) in comparison with canonical models the noncanonical ones predict, at fixed ZAHB effective temperature, a larger envelope mass and therefore overcome the fine tuning of mass loss efficiency necessary for producing EHB stars.

2. Discussion

For comparing in detail theory with observations, Figure 1 shows in the $\log T_e - \log g$ plane a comparison between HB models and current available data for hot HB stars in GCs. For avoiding any misleading effect due to the chemical composition the sample was selected by taking into account data of clusters for which accurate spectroscopic determinations of both Fe and $\alpha$-elements were
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Figure 1. Comparison in the $\log T_e - \log g$ plane between theoretical HB models (solid line: ZAHB, dashed line: central He exhaustion) and empirical data. Spectroscopic measurements were collected by Crocker et al. (1988) for M3, M5, M15, M92 NGC288; de Boer et al. (1995) for NGC6397 and Moehler et al. (1997) for NGC6752. The long-dashed line in the top left panel refers to ZAHB models which account for He extra-mixing.

Solid and dashed lines show the ZAHB and the central He exhaustion of HB models which include new input physics and neglect He extra-mixing (see Bono et al. 1999). Data plotted in this figure suggest that canonical HB models are, within observational errors, in fair agreement with empirical data. At the same time, it is worth noting that gravities predicted by HB models with He extra-mixing are somewhat smaller than the observed gravities in NGC6752, M5, and M3. On the other hand, gravities of canonical models are slightly larger than the empirical ones in the more metal-rich cluster of our sample (NGC288). The main outcome of this comparison is that spectroscopic data marginally support the extra-mixing scenario.

As a further test of the canonical HB evolutionary scenario, Figure 2 shows in the $T_e - \log g$ plane the comparison with field EHB stars collected by Saffer et al. (1994). Data plotted in this figure suggest that within current observational uncertainties - we adopted as conservative estimates $\sigma(g) = \pm 0.2$ dex and $\sigma(T_e) = \pm 1000$ K - theory and observations are in reasonable agreement. In fact, a large number of these objects is located between the He zero age main sequence and the two ZAHBs for $Y_{MS} = 0.23$, $Z=0.0003$ and for $Y_{MS} = 0.28$, $Z=0.02$. The dashed line shows the loci along which HB structures of the former composition exhaust central He burning. The three evolutionary tracks for M=0.508, 0.515 and 0.520 $M_\odot$ suggest that even for post-HB evolutionary phases theoretical predictions agree with observational data.

An interesting feature of EHB stars recently discovered by Kilkenny et al. (1997) and by O’Donoghue et al. (1998 and references therein) is that some
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Figure 2. Comparison in the $T_e – \log g$ plane between theoretical HB models and field EHB stars collected by Saffer et al. (1994). The data (full triangles) for pulsating EC 14026 stars as collected by O’Donoghue et al. (1998) have been also plotted. See text for further details.

of these objects are variable stars. In Figure 2 we also plotted the variables that have been identified up to now. These objects can play a fundamental role in understanding the evolutionary properties of EHB stars. In fact, the comparison between pulsation theory and observations can supply an independent estimate of astrophysical parameters governing the pulsation behavior of these variables. Moreover, the pulsation destabilization could also explain the occurrence of gap(s) along the blue tail. The EHB stars present a very thin envelope and therefore even small perturbations of the outermost layers can cause an increase in the efficiency of mass loss. The plausible consequence of this effect is that the gap(s) might be region(s) of avoidance for EHB stars. Unfortunately, we still lack a firm explanation of the physical mechanisms which drive their pulsation instability. On the basis of a detailed analysis of light curves and of linear pulsation models Stobie et al. (1997) suggested that both radial and nonradial modes should excited but the models they computed are pulsationally stable.

In order to test whether the extra-mixing scenario suggested by Sweigart account for the pulsation behavior and modal stability of these variables we constructed several sequences of linear, nonadiabatic models by adopting a wide range of effective temperatures, luminosities, stellar masses and chemical compositions ranging from $Y=0.24$, $Z=0.0001$ to $Y=0.34$, $Z=0.02$. However, as already found by Stobie et al. (1997), the models are pulsationally stable. These numerical experiments suggest that the He abundance marginally affects the pulsation instability of EC14026 stars, and in turn that the extra-mixing scenario does not help to explain their behavior.

Finally, we mention that a set of models at solar composition constructed by artificially enhancing (by 50%) the opacity bump located close to $2.5 \times 10^5$ K are pulsationally unstable for temperatures ranging from 29000 to 26000 K. A differ-
ent *ad hoc* mechanism for destabilizing these stars was suggested by Charpinet et al. (1996) but we still lack a straightforward understanding of the intimate nature of EC14026 stars. Certainly photometric and spectroscopic surveys of the Galactic halo currently undertaken can supply more tight constraints on the region of the HR diagram in which EHB stars are pulsationally unstable.

**References**

Bono, G., Cassisi, S. & Castellani, V. 1999, *in preparation*

Cassisi, S., Castellani, V., Degl’Innocenti, S. & Weiss, A. 1998, A&AS, 129, 267

Castellani, V. 1999, in Globular Clusters, (Cambridge: Cambridge University Press), in press

Castellani, V., Chieffi, A. & Pulone, L. 1991, ApJS, 76, 911

Castellani, V., Giannone, P., Renzini, A. 1969, Ap&SS, 3, 518

Charpinet, S., Fontaine, G., Brassard, P. & Dorman, B. 1996, ApJ, 471, L103

Crocker, D.A., Rood, R.T. & O’Connell, R.W. 1988, ApJ, 332, 236

de Boer, K.S., Schmidt, J.H.K. & Heber, U. 1995, A&A, 303, 95

Dorman, B., Rood, R.T. & O’Connell, R.W. 1993, ApJ, 419, 596

Dorman, B. et al. 1997, ApJ, 480, 31

Ferraro, F.R., Paltrinieri, B., Fusi Pecci, F., Rood, R.T. & Dorman, B. 1998, ApJ, 500, 311

Grundahl, F., Vandenberg, D.A. & Andersen, M.I. 1998, ApJ, 500, 179

Iben, I.Jr. & Rood, R.T. 1970, ApJ, 161, 587

Kilkenny, D., Koen, C., O’Donoghue, D. & Stobie, R.S. 1997, MNRAS, 285, 640

Kinman, T.D. et al. 1996, AJ, 111, 1164

Liebert, J., Saffer R.A. & Green E.M. 1994, AJ, 107, 1408

Moehler, S., Heber, U. & Rupprecht, G. 1997, A&A, 319, 109

Newell, E.B. 1973, ApJS, 26, 37

O’Connell, R.W. et al. 1997, AJ, 114, 1982

O’Donoghue, D., Koen, C., Kilkenny, D., Stobie, R.S., Lynas-Gray, A.E. & Kawaler, S.D. 1998, Balt.A., 7, 313

Rich, R.M. et al. 1997, ApJ, 484, 25

Saffer, R.A., Bergeron, P., Koester, D. & Liebert, J. 1994, ApJ, 432, 351

Sluis, A.P.N. & Arnold, R.A. 1998, MNRAS, 297, 732

Sosin, C. et al. 1997, ApJ, 480, 35

Stobie, R.S., Kawaler, S.D., Kilkenny, D., O’Donoghue, D. & Koen, C. 1997, MNRAS, 285, 651

Sweigart, A. V. 1997, ApJ, 474, L23

Sweigart, A. V. 1998, in The Third Conference on Faint Blue Stars, ed. A.G.D. Philip, J. Liebert & R.A. Saffer (Cambridge: Cambridge Univ. Press), in press

Sweigart, A. V. & Gross, P.G. 1978, ApJS, 36, 405