Blue Horizontal–Branch Stars: The “Jump” in Strömgren $u$, Low Gravities, and Radiative Levitation of Metals *

F. Grundahl 1, M. Catelan 2,3, W. B. Landsman 4, P. B. Stetson 5, and M. I. Andersen 6

1University of Victoria, Canada
2University of Virginia, USA
3Hubble Fellow
4Raytheon ITSS, NASA/Goddard Space Flight Center, USA
5Herzberg Institute of Astrophysics, Canada
6Nordic Optical Telescope, Spain

Abstract: We study the “jump” in the blue horizontal–branch (BHB) distribution first detected by Grundahl et al. (1998) in the Galactic globular cluster (GC) M13. On the basis of Strömgren photometry for a sample of fourteen GC’s we show that: 1) The jump is best characterized as a systematic shift, on a $u, u-y$ color-magnitude diagram, from canonical zero-age HB (ZAHB) models, in the sense that the stars appear brighter and/or hotter than the models; 2) the jump is a ubiquitous phenomenon, occurring over the temperature range $11,500 \, \text{K} \leq T_{\text{eff}} \leq 20,000 \, \text{K}$; 3) An analogous feature is present in $(\log g, \log T_{\text{eff}})$ diagrams – indicating a common physical origin for the two phenomena; 4) The physical mechanism responsible for the jump phenomenon is most likely radiative levitation of iron and other heavy elements.

1 Introduction

It is of significant interest to understand what factors govern the morphology of the horizontal branch in stellar populations since it is often used as a distance and age indicator. In this contribution we will focus our attention on two problems in our understanding of the HB that have recently become apparent: The occurrence of BHB stars of lower gravities than predicted by canonical models (e.g., Moehler, Heber & de Boer 1995) and the jump in Strömgren $u$ first discovered in M13 by Grundahl, VandenBerg, & Andersen (1998).

Heber, Moehler, & Reid (1997) suggested that helium mixing (Sweigart 1997a,b) in the HB progenitor stars might explain the low gravities problem; a similar suggestion was advanced by Grundahl et al. (1998) in regard to the $u$–jump phenomenon. Given that subsequent

*Based on data collected at the European Southern Observatory (La Silla, Chile) and the Nordic Optical Telescope, Spain
observations showed the \textit{u}-jump to be present in all clusters with a sufficiently hot HB, we decided to undertake a systematic study of this phenomenon. We shall demonstrate, in the following, that the low measured gravities and the \textit{u}-jump are manifestations of one and the same physical mechanism which most likely is radiative levitation of heavy elements. The observations for this project and a more detailed account of the phenomenon are given in Grundahl et al. (1999).

2 The Ubiquitous Nature of the Jump

In Fig. 1 we show the CMDs for all our observed clusters with a BHB. Several important conclusions can be drawn from this Figure: 1) the jump occurs in all clusters, irrespective of any parameter characterizing these such as: metallicity, concentration, luminosity or extent of mixing on the RGB. This makes the helium mixing hypothesis unlikely as the sole explanation for this phenomenon; 2) the “size” of the jump is constant from one cluster to the next; 3) the onset of the jump occurs at $T_{\text{eff}} \approx 11,500 \pm 500$ K for all clusters in the sample (derived from our calibrated photometry and Kurucz color-temperature relations); 3) The cool onset of the jump appears very abrupt. Even in $\omega$ Centauri (which shows a significant metallicity spread) the jump is clearly present and well defined (as predicted in Grundahl et al. 1999); our new photometry for this cluster will be presented elsewhere. We also note that the jump occurs irrespective of the detailed HB morphology, i.e. whether the cluster has a long blue tail or just a stubby BHB.

3 Low Gravities and the Jump Phenomenon

Several of our clusters have had stars with spectroscopically determined gravities published in recent literature. Since our determination of the temperature for the onset of the jump appeared close to the region where gravities lower than predicted by theory were found we have investigated whether the two phenomena are related. Figure 2 shows a plot of the stars in our sample with spectroscopic determinations of their gravity. All stars which are classified as belonging to the jump region (based on the \textit{uvby} photometry) are plotted as black symbols, whereas stars located outside the jump region are plotted as gray symbols. It is apparent from this Figure that stars classified as “jump stars” also have gravities lower than expected from ZAHB models. This clearly shows that \textit{the two phenomena are related on a star by star basis} and hence that the two most likely are manifestations of the same physical phenomenon. As the effect seems unlikely to be caused by stellar evolution (no dependence on mixing history or age is found, both in terms of jump size and location) we strongly suspect that a stellar atmospheres effect is the cause.

4 Radiative Levitation of Metals as an Explanation

Glaspey et al. (1989) obtained high resolution spectroscopy of two BHB stars in NGC 6752 and found that the one which lies inside the jump region at 16,000 K had super–solar iron abundance whereas the one outside had normal abundances compared to the other cluster stars. For field BHB stars Bonifacio et al. (1995) and Hambly et al (1997) find similar trends with large over abundances of some of the heavy elements – the detailed abundance patterns are quite complex.
Figure 1: A mosaic plot showing all our CMDs. The vertical arrows indicate the onset of the jump at its cool end.
These results led Grundahl et al. (1999) to propose that radiative levitation of heavy elements could be the cause for the $u$-jump and low gravities phenomenon. Furthermore simple experiments with enhanced heavy-element abundances, based on Kurucz solar-scaled atmospheres (see Figure 3), succeeded in qualitatively producing a higher flux in $u$ as seen observationally.

Subsequently this hypothesis was given strong observational support by the spectroscopic investigations of Moehler et al. (1999), Peterson (1999), and Behr et al. (1999). These studies showed that several of the heavy elements were overabundant by large factors in the atmospheres of BHB stars in NGC 6752 and M13. Behr et al. further found that the onset of the jump occurs at $T_{\text{eff}} \approx 11,500$ K, in excellent agreement with our estimate. The study of hot HB stars in NGC 6752 by Moehler et al. (1999) further showed that the problem of too low gravities is significantly reduced (although not eliminated) if model atmospheres with appropriately high metallicity are used in the analysis of the spectra.

Given the remarkable similarity of the $u$ (and gravity) jump(s) from one cluster to the next, we suggest that very similar chemical abundance patterns as found by the above authors are likely present in the other systems as well. For detailed quantitative comparisons between observations and theory in what concerns photometry and spectroscopy of blue HB stars lying inside the jump region, we warn that more realistic calculations taking into account the very complicated (but observed) abundance patterns – using, e.g., Kurucz’s ATLAS12 code – will likely be necessary (Grundahl et al. 1999).
Figure 3: The emergent flux in different bandpasses is shown as a function of metallicity for Kurucz model atmospheres with the indicated temperatures. Note that in all cases the largest effect of enhanced abundance occurs in the Strömgren $u$ band, and that there is a marked temperature dependence for filters in the mid-to-far UV (F255W, F160BW, and UIT 1620 Å).
5 Conclusions

We have demonstrated that the $u$-jump discovered by Grundahl et al. (1998) occurs in every globular cluster with HB stars hotter than 11,500 K and that this phenomenon is connected, on a star by star basis, to the “low gravities” found by Moehler et al. (1995). The most likely explanation is that radiative levitation of heavy elements into the stellar atmosphere changes the emergent flux pattern in such a way as to increase the $u$ flux and cause the measured gravities to be too low if these element enhancements are not taken into account. Detailed spectroscopic studies of large samples of stars and theoretical diffusion calculations are urgently needed for further explanation of this phenomenon since radiative levitation is expected to have implications for the interpretation of integrated ultraviolet spectra of old stellar populations – both Galactic and extragalactic (Landsman 1999).

Acknowledgements

Support for M.C. was provided by NASA through Hubble Fellowship grant HF–01105.01–98A awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA under contract NAS 5–26555.

References

Behr B.B., Cohen J.G., McCarthy J.K., Djorgovski S.G., 1999, ApJ 517, L135
Bonifacio P., Castelli F., Hack M., 1995, A&AS 110, 441
Glaspey J.W., Michaud G., Moffat A.F.J., Demers S., 1989, ApJ 339, 926
Grundahl F., VandenBerg D.A., Andersen M.I., 1998, ApJ 500, L179
Grundahl F., Catelan M., Landsman W.B., Stetson P.B., Andersen M.I., 1999, ApJ 524, in press (Oct. 10th issue)
Hambly N.C., Rolleston W.R.J., Keenan F.P., Dufton P.L., Saffer R.A., 1997, ApJS 111, 419
Heber U., Moehler S., Reid I. N., 1997. In: Battrick B. (ed.) ESA-SP 402, HIPPARCOS Venice’97, p. 461
Landsman W. B., 1999. In: Hubeny I., Heap S., Cornett R. (eds.) Spectrophotometric Dating of Stars and Galaxies. San Francisco, ASP, in press (astro-ph/9906123)
Moehler S., Heber U., de Boer K.S., 1995, A&A 294, 65
Moehler S., Sweigart A.V., Landsman W.B., Heber U., Catelan M., 1999, A&A 346, L1
Peterson R. C., 1999, these proceedings
Sweigart A.V., 1997a, ApJ 474, L23
Sweigart A.V., 1997b. In: Philip A.G.D., Liebert J., Saffer R.A. (eds.) The Third Conference on Faint Blue Stars. Schenectady, L. Davis Press, p. 3