Rotation and abundance anomalies in blue horizontal-branch stars

Bradford Behr
McDonald Observatory, University of Texas at Austin, 1 University Station C1400, Austin TX 78712-0259, bbb@astro.as.utexas.edu

Abstract. To address the puzzling photometric properties of horizontal branch stars in Galactic GCs, several different groups have undertaken detailed spectroscopic analyses of individual blue HB stars. Hotter BHB stars show strong metal enhancement and helium depletion, likely due to atomic diffusion, and slow rotation velocities, in contrast to the cooler BHB stars, which have a bimodal distribution of rotation speeds — some of them much faster than expected — but no anomalous abundances. I review the observational results to date, and discuss possible explanations and ramifications of these abundance and rotation characteristics.

1. Introduction

Despite extensive observations and detailed theoretical modelling of post-main-sequence stellar evolution, we still cannot fully explain the color distributions and detailed properties of horizontal branch (HB) stars in globular clusters. The relative number of red versus blue HB stars is primarily a function of a cluster’s metallicity, but the wide variety of HB color morphologies found among Galactic GCs with similar metallicities strongly suggests that some other factor, or combination of factors, must also be at work. Cluster age, helium abundance, stellar kinematics, and binarity have all been considered, but a clearly defined “second parameter” has not yet been identified. Furthermore, high-precision photometry and spectrophotometry reveals further anomalies in HB populations: narrow “gaps” in the distribution of stars along the HB locus (Ferraro et al. 1998), and temperature ranges over which stars are consistently “overluminous” (Grundahl et al. 1999), or have unexpectedly low derived surface gravities (Moehler 2001), compared to canonical HB loci. Evidently, our models do not fully account for all of the relevant properties of these stars.

In order to better understand the characteristics of these stars, several research groups have undertaken detailed high-resolution spectroscopic observations of individual HB stars in metal-poor globular clusters and the field halo population. These investigations have discovered significant variation in both the photospheric chemical abundances and the rotation velocities of these stars, correlating with position along the HB. In this paper, I review the observational work that has been reported to date, discuss possible explanations for these rotation and abundance anomalies, and explore their potential implications for stellar evolution and cluster photometry and kinematics.
2. Abundance and rotation observations

The pioneering high-resolution spectroscopic studies of HB stars were done by Peterson and collaborators (1983ab, 1985ab, 1995), who observed cooler BHB stars in M3, M4, M5, M13, NGC 288, and the nearby field population. They determined projected rotation velocities ($v \sin i$) from the broadening of the metal absorption lines in their spectra, and found several of their target stars spinning as fast as $40 \text{ km s}^{-1}$. Such fast rotation was unexpected, given that these HB stars had evolved from G dwarfs, which lose most of their initial angular momentum to magnetically-coupled winds over their main-sequence lifetimes. Only a fraction of the stars appeared to be spinning so fast; assuming random orientation of rotation axes, M13 and the metal-poor field BHB population appeared to have a bimodal underlying distribution of actual rotation velocities $v_{\text{rot}}$, with roughly one-third of the stars at $v_{\text{rot}} \simeq 40 \text{ km s}^{-1}$ and the other two-thirds at $v_{\text{rot}} \simeq 15$–$20 \text{ km s}^{-1}$. The other clusters seemed to possess only the slowly-rotating stars. Cohen & McCarthy (1997) found similar $v_{\text{rot}}$ bimodality among the cool BHB stars of M92, and Kinman et al. (2000) enlarged the sample of field BHB stars, confirming the existence of both fast and slow rotators among this population. Extending the observations in M13 to higher
Figure 2. Iron and helium abundances of BHB stars as a function of HB position. Horizontal dashed lines indicate the expected abundance level for stars in each cluster, and inverted carets represent upper bounds on abundance. For $T_{\text{eff}} > 11500$ K ($\log T_{\text{eff}} > 4.06$), iron is strongly enhanced and helium is depleted. Data are from Moehler et al. (1999) and Behr et al. (1999, 2000b).

$T_{\text{eff}}$, Behr et al. (2000a) found that the anomalous fast rotators do not appear above $T_{\text{eff}} \simeq 11500$ K, as all of the hotter BHB stars exhibit very slow rotation, $v \sin i < 8$ km s$^{-1}$. A similar temperature dependence was subsequently found in M15 (Behr et al. 2000b) and NGC 1904 (Recio-Blanco et al. 2002). Recio-Blanco also found additional clusters, NGC 2808 and NGC 6093, which appear to possess only the slowly-rotating BHB stars. Figure 1 shows a representative sample of the BHB rotation measurements reported to date, illustrating the variety of $v \sin i$ distributions.

Metallicity differences also appear among HB stars, as first discovered by Glaspey et al. (1989), who analyzed two BHB stars in NGC 6752. Their cooler target, with $T_{\text{eff}} \simeq 10000$ K, had "normal" iron and helium abundances for the cluster, but the hotter star, at $T_{\text{eff}} \simeq 16000$ K, showed an iron abundance 50 times greater than expected, and a helium abundance 40 times lower. More recent observations covering a larger range of $T_{\text{eff}}$ in NGC 6752 (Moehler et al. 1999), M13 (Behr et al. 1999), and M15 (Behr et al. 2000b) confirm these abundance deviations, and reveal the presence of an abundance "jump" at $T_{\text{eff}} \simeq 11500$ K, closely coincident with the transition in rotation velocities. Redwards of the jump temperature, stars show normal cluster abundances, but
bluewards of the jump, the stars are strongly enhanced in iron and most other
metals, and depleted in helium, as illustrated in Figure 2. The magnitude of
the metal enhancement varies from element to element: the iron abundance
increases by 1.5 to 2.0 dex (30 to 100 times), phosphorus increases by 3.0 to 3.5
dex, while magnesium is almost entirely unchanged, remaining at metal-poor
cluster abundance levels over the entire observed temperature range.

3. Diffusion mechanisms

Atomic diffusion appears to be the best explanation for the large variations in
chemical abundances seen among the hotter BHB stars. To explain the anoma-
lessly low helium abundances found among evolved halo stars, Greenstein et al.
(1967) proposed that helium atoms sink under the influence of gravity, diffusing
from the photosphere into the stellar interior, so that the observed helium abun-
dance is lowered. This mechanism would be effective only if the atmosphere were
very stable, since convective or rotational mixing would completely erase the dif-
fusion gradient. Michaud et al. (1983) then pointed out that these same stable
atmospheric conditions would also permit levitation of metal atoms. Driven by
radiation pressure, atomic species with sufficiently large radiative cross-sections
could be lifted from the stellar interior to the photosphere, such that large metal
enhancements appear. Recent models of similar diffusion mechanisms in chemi-
cally peculiar main-sequence Ap stars, by Richer et al. (2000), show abundance
patterns that are qualitatively similar to those we observe: enhancement of
iron, even stronger enhancement of phosphorus, no change in magnesium, and
depletion of helium. Hopefully, these sorts of models will soon be applied to
the specific case of hot BHB stars, to see whether we can quantitatively repro-
duce the spectroscopic observations, and thus verify that radiative levitation
and gravitational settling are responsible for the BHB abundance variations.

We must also explain why the amount of metal enhancement and helium
depletion should change so abruptly as a function of position along the HB. One
likely possibility is that the disappearance of surface convection at a threshold
$T_{\text{eff}}$ is the “switch” which regulates the effectiveness of diffusion. BHB atmo-
sphere/envelope models by Sweigart (2001) show that thin regions of convection
due to H I and He I lie at (or slightly below) the stellar surface for cooler BHB
stars, but when the model $T_{\text{eff}}$ exceeds 12000 K, these convection zones disap-
pear, and the atmosphere is fully radiative in its upper layers. Thus, for stars
hotter than the threshold temperature, diffusion alters the photospheric abun-
dance pattern, while the stars cooler than threshold remain well-mixed, and no
diffusion can take place. It has also been suggested that the abrupt change in
stellar rotation characteristics may determine whether diffusion is effective. If a
star is rotating very quickly, meridional circulation currents can indeed provide
enough mixing to prevent diffusion, but since we see plenty of slowly-rotating
cool BHB stars with normal abundances, rotation is probably not a critical
factor in this regime.

Strong metal enhancement and helium depletion of a star’s photosphere
will alter the atmospheric opacities and emergent spectral energy distribution,
changing the star’s photometric properties. Even before the existence and mag-
nitude of the metallicity jump was fully known, both Caloi (1999) and Grundahl
et al. (1999) proposed that the photometric gaps and jumps that appear along the BHB in many clusters might be due to the sudden onset of diffusion-driven metal enhancements, and initial quantitative tests by Grundahl showed that the observed jumps in Stromgren $u$-band luminosities could be partially reproduced in synthetic photometry by increasing the model atmosphere metallicities. More comprehensive calculations by Hui-Bon-Hoa et al. (2000), which explicitly included element diffusion and stratification, found that metal-enhanced photospheres are consistently bluer in $U - V$ and Stromgren $u - y$ colors than normal metal-poor photospheres, with luminosity jumps similar in size to those observed. The metallicity jump, then, can explain the Stromgren $u$-jump and some of the photometric gaps, such as those around 11000 K in M13 and M80, although cooler gaps like that in M15, and the hotter ones found in NGC 2808, require alternative explanations. The anomalously low log $g$ values measured for hot BHB stars also be partly explained by the metal enhancements, although some degree of helium mixing may be necessary as well (Moehler et al. 2000).

4. Possible explanations of the rotation distribution

The observed distributions of stellar rotation velocities are somewhat more difficult to explain than the abundance variations. Several possible mechanisms have been suggested, but there is no compelling theoretical or observational evidence to indicate which (if any) is correct. Any complete explanation of BHB star rotation must explain three main aspects of the observations: (1) what causes the bimodal distribution of rotation velocities among the cooler stars, (2) why does this bimodality appear only among $\sim \frac{1}{2}$ of the clusters observed, and (3) why do the hotter, metal-enhanced stars all rotate at very low $v_{\text{rot}}$?

Peterson et al. (1983a) and Pinsonneault et al. (1991) suggested that the magnetic braking of a G-type dwarf might only affect its envelope, while its core continues to spin rapidly, retaining much of the star’s primordial angular momentum. After the star arrives on the HB, the core couples to the envelope, spinning up the surface layers to the observed velocities. Sills & Pinsonneault (2000) subsequently refined this scenario, pointing out that if core-envelope coupling takes an appreciable fraction of the star’s HB lifetime, then this could explain the observed bimodality in surface rotation — the fast-rotating stars are those that have been on the HB longer, and have had more time to spin up. Furthermore, they claim, the gradients in mean molecular weight created by helium settling could delay, or even prevent, the transfer of angular momentum from core to envelope, explaining the slow rotation among the hotter stars. This hypothesis predicts that the fast-rotating stars, having spent more time on the HB, will have evolved to slightly higher luminosities. Initial tests (Behr 2000c; Recio-Blanco et al. 2002) show no such correlation between higher rotation and higher luminosity, although the sample sizes and photometric quality are insufficient to rule out this possibility. Helioseismology results (Corbard et al. 1997; Effdarwich et al. 2002) indicate that fast core rotation is not present in the Sun, although some of the Sills & Pinsonneault models demonstrate that faster internal rotation can develop on the RGB as the core shrinks, even given solid-body rotation on the main sequence, so some degree of internal rotation is still a possibility.
Mass loss on the HB provides another means for creating uniform slow rotation among the hot metal-enhanced stars. Vink & Cassisi (2002) describe models of BHB mass loss and resulting loss in angular momentum, and find that mass loss rate is strongly dependent upon photospheric metallicity. They propose that the large metal enhancements that appear for $T_{\text{eff}} > 11500\,\text{K}$ result in a large increase in mass loss, which rapidly removes angular momentum from the star, such that the hotter BHB stars are all slow rotators.

The “excess” angular momentum in the fast-rotating BHB stars could come from an external source, instead of originating within each individual star. Although stellar collisions are quite rare, even in dense cluster centers, close tidal encounters could “spin up” a star, assuming the impact parameter was in the right range. Denser cluster environments do appear to affect the evolution and properties of individual stars, as discussed by Fusi Pecci et al. (1993), Buonanno et al. (1997), and Testa et al. (2001), who note a correlation between higher cluster core densities and the presence of long blue tails in clusters’ CMDs. According to this model, stars in denser environments are more prone to tidal encounters, which enhance mass loss (either via direct tidal stripping, or spin-up), resulting in smaller hydrogen envelopes on the HB, and thus bluer stars.

Alternatively, a stellar companion might provide the additional angular momentum, either through tidal synchronization of the orbital and rotation periods, or via a merger. Stellar mergers are known to happen in GCs, forming fast-rotating blue straggler stars, but the subsequent evolution of these stars would probably not put them on the same HB locus as ordinary single stars. No extended radial velocity monitoring of BHB stars has been performed, so we cannot test for binarity via “Doppler wobble,” but the velocity dispersions of BHB stars closely match those of each cluster population at large (Peterson et al. 1983b), suggesting that large radial velocity variations are not present. Furthermore, BHB stars do not appear to be significantly concentrated towards cluster centers, as many binary star types are. Therefore, stellar binarity does not appear to be common enough to explain the fast rotators.

Smaller companions might still be plausible, however. If a large planet in a close orbit were absorbed by an expanding RGB envelope, it could easily provide sufficient angular momentum to create a fast-rotating BHB star. This scenario was initially suggested by Peterson et al. (1983a), and recent calculations by Soker & Harpaz (2000) and Livio & Soker (2002) show that it is quantitatively plausible. Some “51 Peg-type planets,” with $a \approx 0.05\,\text{AU}$, have been found orbiting stars in the solar neighborhood, but they appear to be quite uncommon in globular clusters, according to the 47 Tucanae transit survey of Gilliland et al. (2000). Planets in wider orbits ($a = 0.2–0.5\,\text{AU}$) cannot be ruled out, and would still be absorbed by the red giant, so the planet hypothesis remains tenable, but there currently exists no independent evidence that planets are sufficiently common in GCs to create the observed fast-rotating BHB population.

5. Summary

Several independent spectroscopic investigations show that photospheric abundances and stellar rotation rates of BHB stars vary significantly as a function of temperature. All BHB stars hotter than $T_{\text{eff}} \approx 11500\,\text{K}$ show metal en-
BHB star rotation and abundance anomalies

Enhancements of 1.5 to 3.5 dex, and helium depletions of \( \sim 2 \) dex. These abundance “anomalies” are most likely due to atomic diffusion processes — radiative levitation of the metals, and gravitational settling of helium — in the stable non-convective atmospheres of the hotter stars. The sudden onset of metal enhancements, possibly due to the disappearance of surface convection, can alter the spectrophotometric properties of the star, thus explaining some, but not all, of the photometric gaps and jumps which have been found in cluster CMDs.

The hotter, metal-enhanced BHB stars all appear to rotate slowly, \( v \sin i < 8 \text{ km s}^{-1} \), in contrast to the cooler \( (T_{\text{eff}} \sim 8000–11500 \text{ K}) \) BHB stars, which show a range of rotation velocities. In some clusters (and the field population), approximately one-third of the cooler stars are rotating at \( v_{\text{rot}} \approx 35–40 \text{ km s}^{-1} \), considerably faster than one would expect for the progeny of slow-rotating main-sequence G stars, while the other two-thirds have more modest rotation rates, \( v_{\text{rot}} \approx 15–20 \text{ km s}^{-1} \). In other clusters, only the slower-rotating stars appear. This distribution of rotation rates might be due to the evolution of internal angular momentum within each star, or may instead be the result of dynamical interactions with other stars or substellar objects within the cluster.

Further BHB rotation observations spanning a range in metallicity, cluster concentration, and cluster size will help to explain the observed \( v \sin i \) distributions. In particular, we need to determine why the presence and peak \( v_{\text{rot}} \) of a fast-rotating population differs from cluster to cluster; if we can correlate stellar rotation with characteristics of the parent clusters, this would provide additional insights into the origin of the fast rotation. With large samples in individual clusters, we could also look for differences in kinematics and radial distribution between the slow and fast rotators. More extensive studies of the field BHB population are also necessary, as these stars exist in a very different dynamical environment from their cluster analogs. The issue of binarity should be tested more directly, with long-term monitoring for radial velocity variations, especially in light of the large binary fractions found among hot evolved halo stars (Saffer et al. 2000; Maxted et al. 2001) and metal-poor field RGB stars (Carney et al., this volume), and future searches for planets around metal-poor GC stars will let us determine whether swallowing of planetary companions is a plausible source of angular momentum. We look forward to continued refinement of stellar models which track the change in internal angular momentum profile as a result of evolution, binary and tidal interaction, and merger events.

References

Behr, B. B., Cohen, J. G., McCarthy, J. K., & Djorgovski, S. G. 1999, ApJ, 517, L135
Behr, B. B., Djorgovski, S. G., Cohen, J. G., McCarthy, J. K., Cote, P., Piotto, G., & Zoccali, M. 2000a, ApJ, 528, 849
Behr, B. B., Cohen, J. G., & McCarthy, J. K. 2000b, ApJ, 531, L37
Behr, B. B. 2000c, Ph.D. thesis, California Institute of Technology
Buonanno, R., Corsi, C. E., Bellazzini, M., Ferraro, F. R., & Fusi Pecci, F. 1997, AJ, 113, 706
Caloi, V. 1999, A&A, 343, 904
Cohen, J. G. & McCarthy, J. K. 1997, AJ, 113, 1353
Corbard, T., Barthomieu, G., Morel, P., Provost, J., Schou, J., & Tomczyk, S. 1997, A&A, 324, 298
Ferraro, F. R., Paltrinieri, B., Fusi-Pecci, F., Rood, R. T., Dorman, B. 1998, ApJ, 500, 311
Eff-Darwich, A., Korzennik, S. G., & Jiménez-Reyes, S. J., ApJ, 573, 857
Fusi Pecci, F., Ferraro, F. R., Bellazini, M., Djorgovski, S. G., Piotto, G., & Buonanno, R. 1993, AJ, 105, 1145
Gilliland, R.L., Brown, T.M., Guhathakurta, P., Sarajedini, A., Milone, E.F., Albrow, M.D., Baliber, N.R., Bruntt, H., Burrows, A., Charbonneau, D., Choi, P., Cochran, W.D., Edmonds, P.D., Frandsen, S., Howell, J.H., Lin, D.N., Marcy, G.W., Mayor, M., Naef, D., Sigurdsson, S., Stagg, C.R., VandenBerg, D.A., Vogt, S., & Williams, M.D. 2000, ApJ, 545, 47
Glaspey, J. W., Michaud, G., Moffat, A. F., & Demers, S. 1989, ApJ, 339, 926
Greenstein, G. S., Truran, J. W., & Cameron, A. G. W. 1967, Nature, 213, 871
Grundahl, F., Catelan, M., Landsman, W., Stetson, P. B., & Andersen, M. I. 1999, ApJ, 524, 242
Hui-Bon-Hoa, A., LeBlanc, F., & Hauschildt, P. H., ApJ, 535, L43
Kinman, T., Castelli, F., Cacciari, C., Bragaglia, A., Harmer, D., Valdes, F. 2000, A&A, 364, 102
Livio, M. & Soker, N. 2002, ApJ, 571, L161
Michaud, G., Vaucclair, G., & Vaucclair, S. 1983, ApJ, 267, 256
Moehler, S., Sweigart, A. V., Landsman, W., Heber, U., & Catelan, M. 1999, A&A, 346, 1
Moehler, S., Sweigart, A. V., Landsman, W., & Heber, U. 2000, A&A, 360, 120
Moehler, S. 2001, PASP, 113, 1162
Peterson, R. C., Tarbell, T.D., & Carney, B.W. 1983a, ApJ, 265, 972
Peterson, R. C. 1983b, ApJ, 275, 737
Peterson, R. C. 1985a, ApJ, 289, 320
Peterson, R. C. 1985b, ApJ, 294, 35
Peterson, R. C., Rood, R. T., & Crocker, D. A. 1995, ApJ, 453, 214
Pinsonneault, M. H., Deliyannis, C.P., & Demarque, P. 1991, ApJ, 367, 239
Recio-Blanco, A., Piotto, G., Aparicio, A., Renzini, A. 2002, ApJ, 572, L71
Richer, J., Michaud, G., & Turcotte, S. 2000, ApJ, 529, 338
Saffer, R. A., Green, E. M., & Bowers, T. P. 2000, astro-ph/0012244
Maxted, P., Heber, U., Marsh, T. R., & North, R. C. 2001, MNRAS, 326, 1391
Sills, A. & Pinsonneault, M.H. 2000, ApJ, 540, 4898
Soker, N. & Harpaz, A. 2000, MNRAS, 317, 861
Sweigart, A. V. 2001, in ASP Conf. Ser., Highlights of Astronomy, Vol. 12, ed. H. Rickman (San Francisco: ASP), in press astro-ph/0103133
Testa, V., Corsi, C. E., Andreuzzi, G., Iannicola, G., Marconi, G., Piersimoni, A.M., & Buonanno, R. 2001, AJ, 121, 916
Vink, J. S. & Cassisi, S. 2002, A&A, 392, 553