Radiative Levitation in Hot Horizontal Branch Stars

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Abstract. There is now considerable evidence that horizontal branch (HB) stars hotter than about 11,500 K experience an enormous enhancement of their photospheric iron abundance due to radiative levitation. In globular clusters, the photospheric iron abundance can reach values of [Fe/H] $\sim +0.3$, or up to two orders of magnitude higher than the cluster iron abundance. Model atmospheres which take into account the iron overabundance are needed for understanding the appearance of the HB in globular cluster color-magnitude diagrams (CMDs), for the derivation of accurate luminosities, gravities and masses, and for the ultraviolet spectral synthesis of old, metal-poor stellar populations.

1. Introduction

Grundahl et al. (1999) recently suggested that radiative levitation of heavy elements to supersolar abundances occurs for globular cluster HB stars hotter than about 11,500 K. This suggestion was based on the following evidence:

- Grundahl et al. obtained Str"omgren $u$, $u-y$ CMDs of 14 globular clusters and found evidence for a ubiquitous “jump” at about $T_{\text{eff}} = 11,500$ K, in the sense that stars hotter than this temperature are about 0.25 mag brighter in Str"omgren $u$ than predicted by HB models. This jump is not present in ultraviolet CMDs of globular clusters obtained with HST or the Ultraviolet Imaging Telescope (UIT), which suggests that it is due to an atmosphere effect (causing a redistribution in the flux), rather than to a change in the bolometric luminosity. (The presence of a luminosity jump is difficult to discern at wavelengths longer than Str"omgren $u$ because the HB becomes “vertical” in the CMD, and the effects of changes in luminosity cannot be distinguished from changes in temperature.)

- As summarized by Moehler (1999), the derived gravities of HB stars with $11,500 < T_{\text{eff}} < 20,000$ K are consistently found to be about 0.2 dex lower than predicted by canonical HB models. Grundahl et al. performed simple experiments with Kurucz model atmospheres which suggested that both the gravity anomaly and the brightening in Str"omgren $u$, could be explained if the HB photosphere had a supersolar metallicity, rather than the metallicity of the cluster.

- Hot HB stars in globular clusters are observed to show strong depletions of helium (e.g. Moehler et al. 1997). The early theoretical work of Michaud et
Al. (1983) suggested that if the HB atmosphere is stable enough to allow for the gravitational settling of helium, then overabundances of heavy elements by factors of $10^3 - 10^4$ might be expected due to radiative levitation.

- Helium-depleted field HB stars hotter than 11,500 K show unusual abundance patterns, and have higher iron abundances than observed in cooler HB stars. In particular, in the well-studied field HB star Feige 86 (Castelli et al. 1997), the elements lighter than sulfur are depleted (with the exception of phosphorus, with $[\text{P/H}] = +1.8$), while iron-peak elements are slightly supersolar ($[\text{Fe/H}] = +0.4$), and the heavy metals are strongly overabundant (e.g. $[\text{Au/H}] = +4.0$). Glaspey et al. (1989) reported an overabundance of iron by a factor of 50 (and a helium depletion) in a hot HB star in NGC 6752 (CL 1083) with $T_{\text{eff}} = 16,000$ K.

With the exception of the single star in NGC 6752 studied (at low S/N) by Glaspey et al., all the evidence for an iron enhancement in globular cluster HB stars discussed by Grundahl was indirect. However, independent of Grundahl et al. work, Behr et al. (1999) were using the Keck HIRES echelle spectrograph to study abundances in 13 hot HB stars in M13. Their results provide striking direct evidence for radiative levitation in globular cluster hot HB stars, and for abundance patterns similar to those observed in Feige 86. The iron abundances in the M13 HB stars hotter than 11,500 K are about +2.0 dex higher than in stars cooler than the jump temperature. Phosphorus is also enhanced ($[\text{P/H}] = +1.0$), but the magnesium abundances ($[\text{Mg/H}] \sim -1.5$) show no change across the jump temperature. Subsequently, Moehler et al. (1999) used medium ($\sim 2.6$ Å) resolution spectroscopy to show the presence of a similar jump to supersolar iron abundances (with Mg remaining at the cluster abundance) in NGC 6752. In addition, Moehler et al. were able to explicitly show that most – though not all – of the discrepancy between the derived gravities and canonical models could be removed if the Balmer lines were analyzed using appropriately metal-rich atmospheres. We hope to further explore the appropriate model atmospheres for hot HB stars using our Cycle 8 HST program (8256) to obtain STIS ultraviolet spectra of nine HB stars in NGC 6752 spanning the temperature range of 10,000 K < $T_{\text{eff}}$ < 24,000 K.

The sample of stars with abundances determined by Behr et al. or Moehler et al. does not include any stars hotter than 20,000 K. Peculiar abundance patterns are known to exist in the sdB stars (e.g. Lamontagne et al. 1987), and pulsation studies indicate the presence of radiative levitation of iron within the envelope (Charpinet et al. 1997). However, the photometric discrepancy with canonical models in Strömgren $u$ discussed by Grundahl et al. decreases for $T_{\text{eff}} > 20,000$ K, and the field sdB stars do not show the strong overabundances seen in cooler (and lower gravity) HB stars, such as Feige 86. Thus, we suggest that the most dramatic effects of radiative levitation occur in the temperature range 11,500 K < $T_{\text{eff}}$ < 20,000 K.

The presence of strong abundance anomalies in hot HB stars complicates the derivation of accurate luminosities, gravities, and masses, and the analysis of the integrated ultraviolet spectra of old, metal-poor stellar populations. But these abundance anomalies also mean that the HB of globular clusters will likely provide a superb laboratory for studying radiative levitation and diffusion pro-
cesses in the outer atmospheres of hot stars. The HB stars in a globular cluster have known initial abundances, and provide a populous sample for studying the effects of temperature, initial metallicity, and rotation on the photospheric abundances resulting from radiative levitation. (The uniformity of the Strömgren $u$ jump indicates that the effects of radiative levitation must be rapid compared to the HB lifetime of about $10^8$ yr.)

In analogy to the HgMn stars (e.g. Leckrone et al. 1999), the rough abundance pattern observed in hot HB stars can be understood as being due to saturation of radiative forces in the more abundant lighter elements. However, other effects reported by Behr et al. and Moehler et al. have no ready explanation, including the increased helium depletion with increasing $T_{\text{eff}}$, and in particular, the abruptness of the transition to supersolar iron abundances at 11,500 K. An important clue might be provided by the observation by Behr et al. of a low rotation ($v \sin i < 6$ km s$^{-1}$) in stars hotter than the jump, since rotationally-induced turbulence can inhibit diffusion processes. But this only moves the problem one level deeper, since the origin of the abrupt change in rotational velocities would still be unknown.

2. Implications

What are the implications of the discovery of radiative levitation for the outstanding problems in the studies of globular cluster HB stars? First, the discovery of radiative levitation has no direct implications for the age or distance scale of globular clusters, since hot HB stars have not been used as absolute calibrators. Similarly, the discovery of radiative levitation in hot HB stars does not answer the question of why some HB stars are hot, or, more generally, on the origin of the HB morphology (e.g. the second parameter problem).

Another outstanding problem in HB studies is the origin of “gaps” in the temperature distribution of HB stars, and in this case, radiative levitation might have a contributing role for any gap located near 11,500 K (such as the G1 gap discussed by Ferraro et al. 1998). In certain bandpasses, the sudden change in photospheric abundances near this temperature might shift the positions of stars along the HB. For example, in a $y$, $u-y$ diagram, the brightening in Strömgren $u$ with the onset of radiative levitation could induce a gap in the HB distribution at 11,500 K.

Although the dominant implications of radiative levitation are for the HB stellar atmosphere, in principle, the changes in the radial chemical profile could alter the bolometric luminosities and lifetimes computed in HB interior models. This effect is likely to be small, although Seaton (1997) does warn that the surface abundance changes patterns in the HgMn stars are probably a manifestation of radiative diffusion processes deep in the stellar envelope, which (through the modified opacities) can alter the stellar structure.

Hot HB stars are one of the few potential ultraviolet sources in an old stellar population, and thus the discovery of radiative levitation has significant implications for the ultraviolet spectral synthesis of old, metal-poor systems. The implications are less for a metal-rich population for two reasons: first, the metallicity enhancement due to radiative levitation is less pronounced for metal-rich stars, and second, fewer hot HB stars are expected in a metal-rich system,
since the HB is expected to bifurcate into either very hot (> 20,000 K) or cool HB stars (Dorman, Rood, & O’Connell 1995). Spectral synthesis models of the ultraviolet upturn in elliptical galaxies computed in either the metal-poor or the mixed metallicity scenarios discussed in Yi et al. (1999), should probably be performed using metal-rich atmospheres for metal-poor HB stars with $T_{\text{eff}} > 11,500$ K. In particular, the use of metal-rich model atmospheres might help suppress the model flux in the 1800 – 2500 Å spectral region, and improve the agreement of the metal-poor models shown in Yi et al. with the observed spectra of ellipticals.

Finally, the empirical finding of Behr et al. (1999) and Moehler et al. (1999) that Mg abundances are unaltered by diffusion processes suggests that Mg is the most reliable abundance indicator for field hot HB stars. For example, while most the of the abundances derived in Feige 86 by Castelli et al. (1997) have been modified by diffusion processes, the magnesium abundance ($[\text{Mg/H}] = -0.64$) probably provides a good measure of the stellar metallicity.

Acknowledgments. I thank my collaborators on this topic, including M. Catelan, F. Grundahl, T. Lanz, S. Moehler, C. Proffitt, and A. Sweigart

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