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DIFFUSION IN THE ATMOSPHERES OF BLUE HORIZONTAL-BRANCH STARS

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ABSTRACT

We investigate the effects of diffusion in the atmospheres of hot horizontal-branch stars using a model atmosphere code including diffusion self-consistently. Equilibrium stratifications (i.e., for which the diffusion velocity equals zero in each layer) are computed for models of effective temperatures between 10,000 and 25,000 K. The stratified models provide much better agreement with many observational features [jump in the (u, $u-y$) color-magnitude diagram, gaps, lower spectroscopic gravities] in comparison with classical horizontal-branch models. The observed abundance anomalies are also consistent with the amounts that can be supported in the atmospheres.

Subject headings: diffusion — globular clusters: general — stars: abundances — stars: atmospheres — stars: chemically peculiar — stars: horizontal-branch

1. INTRODUCTION

Blue horizontal branches (HBs) of globular clusters (GCs) often have anomalous morphologies in comparison to theoretical sequences. For instance, gaps are seen along the blue tail (see the review of Moehler 2000); jumps in the Strömgren (u, $u-y$) color-magnitude diagram (CMD) are obvious in all the clusters observed by Grundahl et al. (1999). Spectroscopic gravities of these blue HB stars are also lower than those predicted by classical HB models (e.g., Crocker, Rood, & O'Connell 1988; Moehler, Heber, & de Boer 1995), at least for the metal-poor clusters (Moehler, Sweigart, & Catelan 1999a).

Among the possible explanations, recent works suggest that these peculiarities may be due to abundances departing strongly from those of the cluster (Grundahl et al. 1999; Caloi 1999; Moehler et al. 1999b). Abundance anomalies in GC blue HB stars, such as helium deficiencies (Baschek 1975) and enhancement of heavy elements (Glaspey et al. 1989; Behr et al. 1999), are likely to be created by radiative diffusion (e.g., Greenstein, Truran, & Cameron 1967; Michaud, Vauclair, & Vauclair 1983; Glaspey et al. 1989).

Diffusion can have effects on the abundances only if hydrodynamical processes are small enough in the medium. In particular, Michaud (1982) showed that, in main-sequence stars, meridional circulation could prevent chemical separation if the rotation velocity was too high. In M13, the rotation velocity decreases abruptly beyond 11,000 K (Peterson, Rood, & Crocker 1995; Behr et al. 2000b) and the superficial layers of hot HB stars should be much more stable than those of cooler objects. This change occurs at a temperature strikingly close to that of the onset of abundance anomalies in the same M13 stars (Behr et al. 1999) and to those of the "u-jump" (Grundahl et al. 1999) and "G1" gap (Ferraro et al. 1998) in this cluster, which suggests that these behaviors are closely related. A link between low rotation and abundance anomalies is also present in M15 (Behr, Cohen, & McCarthy 2000a).

In this Letter, we show that diffusion in the atmosphere of hot HB stars could explain, at least qualitatively, many of the observational features. The main advantage of this model is that there are no free parameters other than the fundamental ones (T_{eff}, $\log g$).

2. SELF-CONSISTENT MODEL ATMOSPHERES INCLUDING DIFFUSION

For the computation of our models, we use a modified version of the multipurpose stellar atmosphere code PHOENIX (Hauschildt et al. 1996, 1997a, 1997b; Baron & Hauschildt 1998; Hauschildt & Baron 1999) in which diffusion has been included. Here, we will only outline the main features of the code; details will be given in a forthcoming paper (A. Hui-Bon-Hoa et al. 2000, in preparation).

2.1. *Radiative Accelerations*

The radiative accelerations (g_{rad}) are calculated for all the elements available in PHOENIX using the opacity sampling method, following the approach used for the resolution of the radiative transfer (for a discussion about g_{rad}'s obtained through opacity sampling, see LeBlanc, Michaud, & Richer 2000). The mutual influence of abundance variations among the different elements is thus considered. Line as well as continuous absorptions are taken into account. The momentum sharing among the various ionization stages of an element, the so-called redistribution (Montmerle & Michaud 1976), is treated according to the formalism of Alecian & Vauclair (1983). Since we have presently implemented the detailed calculation of radiative accelerations only for LTE species, the ionization/recombination rates are estimated using the method of Hui-Bon-Hoa, Alecian, & Artru (1996), with radiative processes only. Redistribution may thus be underestimated, but the contribution of collisional processes is negligible in the upper part of the atmospheres, where redistribution is the most efficient.

2.2. *Stratification Profiles*

Studying abundance stratification due to diffusion requires the consistent resolution of radiative transfer and continuity equation. This kind of calculation is not available yet in stellar

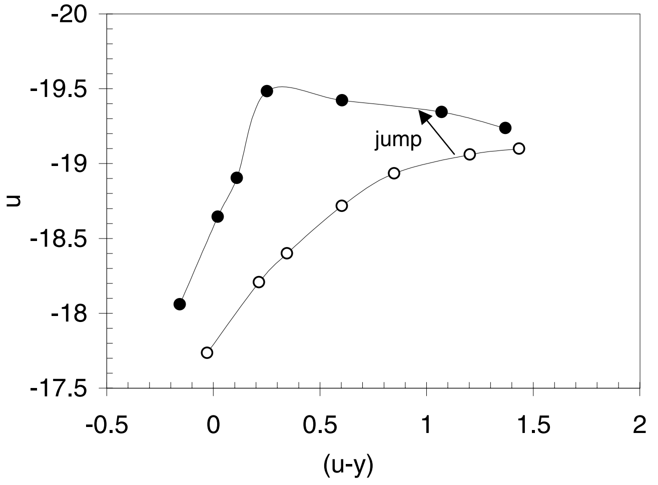

FIG. 1.—Synthetic (u, $u-y$) color-magnitude diagram showing the sequence of the homogenous, cluster abundance models (*open circles*) and that of the stratified ones (*dots*). Units are magnitudes; arbitrary origin for the ordinates. For each sequence, from right to left, are the models with $T_{\rm eff}$ = 10,000, 11,000, 13,000, 15,000, 18,000, 20,000, and 25,000 K. The arrow indicates the location of the jump if diffusion becomes suddenly efficient around $T_{\rm eff}$ = 11,500 K.

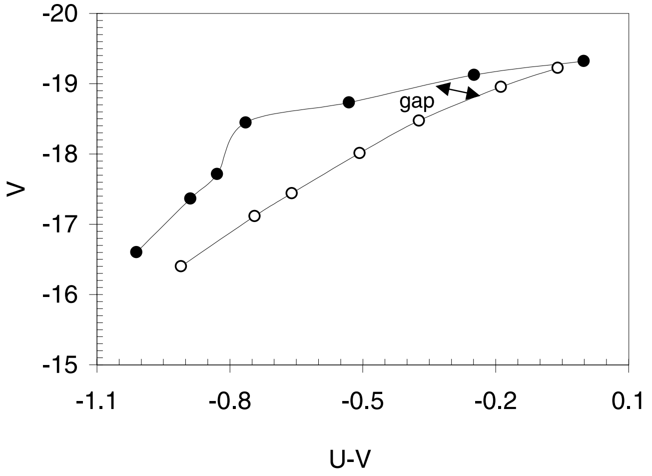

FIG. 2.—Same as Fig. 1 but in the (V, $U-V$)-plane. The line ended by arrows indicates the location of the gap if diffusion becomes suddenly efficient around $T_{\rm eff}$ = 11,500 K.

atmospheres. Nevertheless, we can estimate for each element the amount that can be supported by the radiative accelerations in each part of the atmosphere by computing the so-called equilibrium stratification, i.e., that for which the diffusion velocity equals zero in each layer. Since we do not consider the continuity equation, the actual stratification could be very different.

When the concentration gradients are not too strong, canceling the diffusion velocity reduces to the balance of the radiative forces, gravity, and the electrical forces (estimated using Burgers 1960) for each element. This criterion is introduced in the code as an additional constraint for the building of the model. The abundance changes are therefore considered consistently in the computation of the structure. Calculations were stopped whenever the contribution of the gradients appeared to be nonnegligible in the diffusion velocity, but, in most cases, the stratification profile is then very near equilibrium. We found that the photometric properties depend mostly on the abundances in the line-forming region so that the details of the abundance profile have little influence. Also, the stratification profiles are nearly independent of the initial (homogenous) composition so that there are only two free parameters (i.e., $T_{\rm eff}$ and $\log g$).

2.3. *Zero-Age Horizontal-Branch Models*

Two grids of zero-age horizontal branch (ZAHB) star atmospheres were computed, one with homogenous composition ([He/H] = 0.0; [M/H] = −1.5; [O/Fe] = 0.5, hereafter the “cluster” abundances), the other with stratified abundances. Seven models were considered in each sequence, with $T_{\rm eff}$ ranging from 10,000 to 25,000 K. At a given $T_{\rm eff}$, $\log g$ is set following the ZAHB of VandenBerg et al. (2000).

3. RESULTS AND DISCUSSION

3.1. *Abundances*

Abundances were recently determined in a sample of blue HB stars in M13 (Behr et al. 1999) and M15 (Behr et al. 2000b). For each metal, the amount that can be supported in the atmosphere is much greater than observed in most cases, whatever the temperature, showing that these overabundances can be created by radiative diffusion. For instance, [Fe/H] in the line-forming region of the stratified models is between 1.0 and 1.5. [Mg/H] varies from −0.1 in the coolest models to −2.0 at 25,000 K. As observed, helium is not supported by the radiative accelerations and settles gravitationally. That all the M13 and M15 stars below $T_{\rm eff} \simeq$ 12,000 K have the cluster pattern is certainly due to mixing mechanisms strong enough to prevent chemical separation since the radiative accelerations are still able to support strong metal overabundances. A more detailed discussion between observations and theoretical results requires much more sophisticated models that take explicitly the mass conservation of each element into account.

3.2. *Photometry*

Grundahl et al. (1999) found a “jump” in the (u, $u-y$) CMD which appeared in all the clusters they studied. Stars hotter than approximately 11,500 K are above the sequence defined by canonical ZAHB models. To verify if our stratified models could account for this, we computed with modified versions of the Kurucz (1993) codes synthetic Strömgren *uvby* colors, which were normalized using the PHOENIX Vega model (Hauschildt et al. 1999). The radii were derived considering a typical mass of 0.6 $M_\odot$ (according to canonical models, e.g., Dorman, Rood, & O’Connell 1991).

The stratified model sequence lies clearly above that with homogenous, cluster abundances (see Fig. 1). If we assume that the onset of abundance anomalies spans a very narrow range in $T_{\rm eff}$, as suggested by the results of Behr et al. (1999, 2000a), then a jump would occur, stars below the jump temperature (11,500 K, Grundahl et al. 1999) being on the homogenous sequence whereas hotter ones follow the stratified branch. The shift in u-magnitude for a given $u-y$ index is of similar strength as those observed, except around $u-y$ = 0.3 where it is slightly greater. Below the jump temperature, the stratified model sequence is still above the homogenous one, which suggests that diffusion is hampered by mixing processes for the cooler stars. As observed, a shift remains for stars hotter than 20,000 K, but to a lesser extent.

Gaps in the (V, $B-V$)-plane are reported in several GCs (see the review of Moehler 2000). They appear like underpopulated (or unpopulated) parts of the HB. Gaps are also observed in the (V, $U-V$)-plane (Ferraro et al. 1998). Figure 2 shows the two synthetic sequences in the (V, $U-V$) CMD (colors derived as above). The two sequences are closer to each other than in the (u, $u-y$)-plane, but a shift between models of same temperature is visible especially around 15,000 K. Again, a gap may appear if diffusion becomes efficient in a small temperature range (around 11,500 K), with a size similar to those observed.

That only the total opacity in each bandpass has an influence, regardless of the detailed abundance pattern, explains the much better quantitative agreement for photometry in comparison to individual abundances.

3.3. *Spectroscopic Gravities*

Spectroscopic gravities derived using the Balmer lines are lower than those predicted by canonical ZAHB models for stars with temperatures between 11,000 and 20,000 K in metal-poor GCs (e.g., Crocker et al. 1988; Moehler et al. 1995). By synthesizing Balmer lines with PHOENIX, we find that stratified models yield lower gravities than the homogenous ones with cluster abundances at fixed temperature. The value of $\log g$ is reduced by about 0.5 dex around 15,000 K, close to the difference between canonical models and observed values at this temperature. The fact that the total opacity (through the atmospheric structure) influences the Balmer line formation explains the better agreement with observations compared to the detailed abundances.

That the metal-rich GC HB stars have spectroscopic gravities in agreement with those predicted by canonical models (Moehler et al. 1999a) may reflect homogenous abundances. All the observed stars have $T_{\rm eff}$ below 13,000 K, and the onset of abundance anomalies may occur at higher temperatures at these metallicities. Abundance determinations could help clarify the situation.

4. CONCLUSION

We have shown that diffusion in the atmospheres of blue HB stars can explain many observational facts simultaneously, with a model that only involves first principles. The observed photometric jumps and gaps and spectroscopic gravity anomalies are shown to be due to anomalous abundances produced by radiative diffusion. However, the details of the observable abundances need more sophisticated models including the time-dependent calculation of the stratification for the mass conservation to be considered properly. Such developments are currently underway.

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