

Horizontal branch stars as AmFm/HgMn stars

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Abstract. Recent observations and models for horizontal branch stars are briefly described and compared to models for AmFm stars. The limitations of those models are emphasized by a comparison to observations and models for HgMn stars.

Key words: Galaxy: globular clusters – stars: Population II – stars: horizontal branch – stars: abundances – diffusion – acceleration of particles

1. Introduction

At around 16 000 K, the T_{eff} where the horizontal branch (HB) crosses the main-sequence, HB stars have the same T_{eff} and $\log g$ as HgMn stars. Both have very shallow surface convection zones and they appear to have some abundance anomalies in common (Sargent, Searle 1967; 1968). At slightly cooler T_{eff} , HB stars have a smaller $\log g$ and their convection zones become as deep or even deeper than those of AmFm stars. On the main-sequence, stellar evolution models assuming a mixed outer zone have been relatively successful at explaining AmFm stars (Richer *et al.*, 2000; Michaud *et al.*, 2005). Detailed models for HgMn stars are more complex and have involved NLTE calculations of individual species (for a review see Michaud 1981; Michaud *et al.*, 1974; Proffitt *et al.*, 1999).

We first very briefly (§ 2) describe stellar evolution calculations done with all effects of atomic diffusion including radiative accelerations, g_{rad} . We then show applications to Pop II stars (§3). We will briefly describe recent observations of abundance anomalies in HB stars and what fraction of them can be explained by stellar evolution models with a mixed outer zone (§3.2.2), a model similar to that used for AmFm stars. After a few examples of results for AmFm and HgMn stars (§4), the role of chemical differentiation in the atmosphere of HB stars is discussed in §5 as well as the potential role of rotation in reducing anomalies, thus linking HB and HgMn stars.

2. Stellar evolution with radiative accelerations

The particle transport equations are introduced into a stellar evolution code which was described in Vandenberg (1985), Proffitt and Michaud (1991), and

Proffitt (1994). For each species one adds a force equation (eq. [18.1] of Burgers 1969) and a heat equation (eq. [18.2] of Burgers). There are consequently two coupled differential equations for each of the 28 included species. Similar equations are written for electrons. It is generally assumed that each atomic species can be treated locally as being in an average state of ionization. One needs to know Z_i , an appropriate mean of the number of lost electrons.

The dominant term for each species contains $g_{\text{rad}}(A) - g$ as a factor, where $g_{\text{rad}}(A)$ is an appropriate average of the radiative acceleration over the states of ionization of element A . Over most of the stellar interior and for most of the evolution, it dominates transport even though the electric field, “diffusion” and thermal diffusion terms are also included in the calculations and are important for part of the evolution in some stars.

Rosseland opacities, mean ionic charges, and mean radiative forces are calculated using the same interpolation method, based on the principle of corresponding states described in §2.2 of Rogers and Iglesias (1992); see in particular their equations (4) to (6). Interpolation weights are determined for a subset of the data grid, and used to interpolate locally all these variables.

In first approximation, evaluating $g_{\text{rad}}(A)$ amounts to calculating the fraction of the momentum flux that each element absorbs from the photon flux. In stellar interiors, it takes the form:

$$g_{\text{rad}}(A) = \frac{L_r^{\text{rad}}}{4\pi r^2 c} \frac{\kappa_R}{X_A} \int_0^\infty \frac{\kappa_u(A)}{\kappa_u(\text{total})} \mathcal{P}(u) du \quad (1)$$

where most symbols have their usual meaning. The quantities $\kappa_u(\text{total})$ and $\kappa_u(A)$ are respectively the total opacity and the contribution of element A to the total opacity at frequency u , with u and $\mathcal{P}(u)$ given by:

$$u = \frac{h\nu}{kT} \quad (2)$$

and

$$\mathcal{P}(u) = \frac{15}{4\pi^4} u^4 \frac{e^u}{(e^u - 1)^2}. \quad (3)$$

The calculations of $g_{\text{rad}}(A)$ involve carrying out the integration over the 10^4 u values for each atomic species, A . It implies using a 1.5 Gigabyte spectrum data base from OPAL. The integrations must be repeated for each atomic species, at each mesh point (typically 2000 in our models) and at each time step (typically 10^4 up to the giant branch). The Rosseland average opacity is also continuously recalculated making these calculations fully self consistent with all composition changes.

3. Pop II and HB stars

Evolutionary calculations have been carried out for a large number of masses and metallicities (Richard *et al.*, 2002 a, b). These have in particular been used

to determine the age of M92, one of the oldest globular clusters, to be 13.5 Gyr, and to constrain the Li abundance to be expected from stellar evolution in the oldest stars. Both were compared to observations of WMAP (Richard *et al.*, 2005; VandenBerg *et al.*, 2002).

3.1. From the Main Sequence to the tip of the Giant Branch

Here, we follow a $0.8 M_{\odot}$ model with $Z = 10^{-4}$ from the zero age main-sequence to the middle of the HB. Its metallicity allows a comparison to observations in the globular cluster M15. The evolution is carried out without the adjustment of any parameter except in so far as the mixing length was determined to fit the solar model (Turcotte *et al.*, 1998).

During main-sequence evolution, concentration variations develop throughout the star. At turnoff, a $0.8 M_{\odot}$ star has $T_{\text{eff}} \sim 6500$ K and an age ~ 11.5 Gyr (Richard *et al.*, 2002 b). The concentration variations caused by atomic diffusion extend over 30% of the radius at the level of a factor of 1.5 in contrast and over 60% of the radius at the level 1.2 in contrast. There are overabundances of all atomic species from Na to Ni in the atmospheric regions but overabundance factors vary among the species. Some of those abundance anomalies may have been seen in M92 by King *et al.* (1998) but at the limit of detection so that this result requires confirmation since the signal to noise ratio was not quite satisfactory. Metals pushed from the deeper interior also accumulate within the star where $g_{\text{rad}} - g \sim 0$. This occurs progressively deeper in, as one considers species with larger atomic numbers from S to Ni, since a given electronic configuration occurs progressively deeper in the star as the atomic number increases.

As the evolution proceeds on the subgiant and giant branches, dredge up occurs and mixes some 58 % of the star. The abundance anomalies are largely but not completely eliminated. At the He flash, there remains a 0.04 dex difference in metal abundance concentration between the surface and the core and a $0.003 M_{\odot}$ difference in helium core mass between a model calculated with and without diffusion.

3.2. Horizontal Branch stars

The transition to the HB was carried out as described in Michaud *et al.* (2007): a fraction of the envelope mass was removed and the star was reconverged on the HB following approximately the procedure used by Sweigart (1987). On the HB there are effects of diffusion in three regions of the star: just outside the He burning core, just below the H burning shell and to produce surface abundance anomalies. The first two are discussed in § 3.2.1 and the last one in § 3.2.2.

3.2.1. Structural effects of diffusion

In canonical stellar evolution it has been standard practice since the suggestion of Paczyński (1970) to assume that the He burning core is extended by

overshooting or penetration in order to maintain convective neutrality at the boundary. Since the opacity of carbon rich material is larger than that of He rich material, the radiative gradient increases in the core as He burning transforms He into C. If the core boundary is stationary, strong superadiabaticity develops at the boundary. It has been customary to assume that this causes overshooting. This process is however poorly understood (see Sweigart, 1994) and its efficiency is essentially unknown. In stellar evolution with atomic diffusion, this superadiabaticity does not develop. Instead atomic diffusion, even in the absence of overshooting, is sufficient to cause core expansion and maintain convective neutrality at the boundary (see Fig. 10 of Michaud *et al.*, 2007). This does not prove that overshooting does not exist, but it is not necessary to ascribe to it a significant mixing efficiency since the transport it was assumed to carry can be done by atomic diffusion when it is properly included.

The second structural effect of atomic diffusion is related to H burning. Atomic diffusion of the H which is burning in the shell causes an extension inward of this shell. Hydrogen makes contact with C that was synthesized during the He flash. It leads to an increase in H burning and so of luminosity but only of ~ 0.01 dex.

Those structural effects of diffusion are caused by *atomic* diffusion. They are not influenced by the turbulent transport that was introduced in the outer envelope as described in §3.2.2.

3.2.2. Surface abundance anomalies

Since HB stars are Pop II stars that just left the giant branch of globular clusters, they are all expected to have the same concentration of metals, at least of those heavier than Al (Gratton *et al.*, 2004). The concentration of CNO and other relatively light species might show small variations but Fe is not expected to be affected. Michaud *et al.* (1983b) however suggested that g_{rad} should lead to overabundances of at least some metals in those stars where settling causes underabundances of He. Glaspey *et al.* (1989) have confirmed the overabundance of Fe in one star of one cluster but at the limit of detection and this observation required confirmation. This prediction has now been confirmed in many clusters (Behr *et al.*, 1999; Moehler *et al.*, 2000; Fabian *et al.*, 2005; Pace *et al.*, 2006) but in particular by Behr (2003) for M15. Overabundances of Fe by factors of 50–100 are seen in nearly all HB stars with $T_{\text{eff}} > 11\,500$ K while the cooler ones have the same Fe abundance as the cluster’s giants (see Fig. 2).

In stellar evolution calculations, the surface concentrations can be affected by the exterior boundary conditions. In the calculations of Michaud *et al.* (2008), the simplest assumption was made, that of a mixed outer zone without any mass loss. The concentration variations within a $0.61 M_{\odot}$ HB star, 30 Myr after ZAHB, are illustrated in the left panel of Fig. 1. One notes that, in this HB model, all species more massive than O, except S, are overabundant in the external region. There is a second abundance peak of metals that is progressively

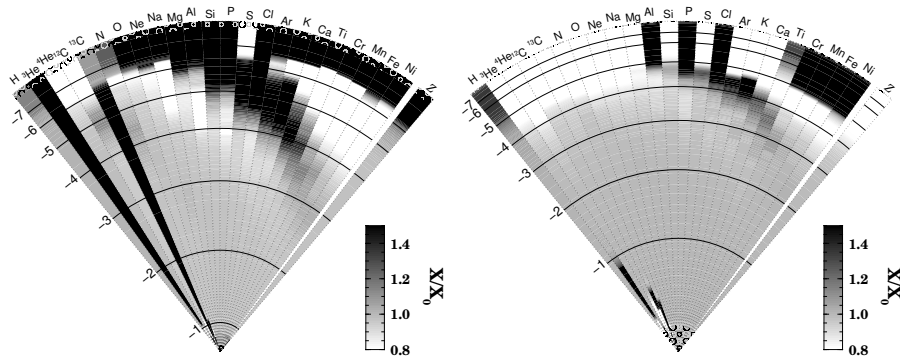


Figure 1. Concentration variations for all calculated species, *left panel*, in a $0.61 M_{\odot}$ model after 30 Myr on the HB ($T_{\text{eff}} \sim 12400$ K) and, *right panel*, in a $2.0 M_{\odot}$ Pop I star ($T_{\text{eff}} \sim 8005$ K) after 616 Myr on the main-sequence as appropriate for a Hyades star. The gray scale is adjusted so that an overabundance by a factor of 1.5 or more appears black in both cases while an underabundance by a factor of 0.8 or less appears white. The radial scale is linear in r . Horizontal lines indicate the mass of the spherical shell outside a certain radius (Δm) labeled by $\log(\Delta m / M_*)$. The HB model is more concentrated since there is about $\log(\Delta m / M_*) = -2$ outside of the fractional radius where there is $\log(\Delta m / M_*) = -1$ in the main-sequence model. This leads to larger effects of diffusion on the HB. The outer 50% by radius is affected by diffusion in the HB model ($\log(\Delta m / M_*) = -3$) while it is the outer 25 % by radius in the Pop I model ($\log(\Delta m / M_*) = -3$) even if 20 times longer was available to the Pop I model.

deeper in the star from S (at $\log(\Delta m / M_*) \sim -5$) to Fe (at $\log(\Delta m / M_*) \sim -3$). This is caused by g_{radS} being linked to electronic shells and heavier elements getting into a given electronic shell at higher T .

The density dependence of the turbulent diffusion coefficient was adjusted to reproduce approximately the observations of Fe in one of the stars observed by Behr (2003) in M15. In practice, the outer envelope ($\log(\Delta m / M_*) \sim -7$ corresponding to the region above $T \sim 10^5$ K) was mixed. The same model reproduced reasonably well the observations in other high T_{eff} stars of that cluster as may be seen in Fig. 2. Furthermore, as may be seen in Fig. 11 and 12 of Michaud *et al.* (2008) the other anomalies are also reasonably well reproduced. This is a striking confirmation of the role of g_{radS} in HB stars.

Some hints as to possible additional separation mechanisms may be suggested by the anomalies which are not as well reproduced. In particular as may be seen from the right panel of Fig. 2, He is expected to be underabundant with the turbulence model determined by the Fe abundance and indeed it is observed to be underabundant. But the observed underabundance is larger than expected from the calculations. If one assumes that the mixed zone only comprises the region above $T \sim 30000$ K, expected He underabundances are increased by

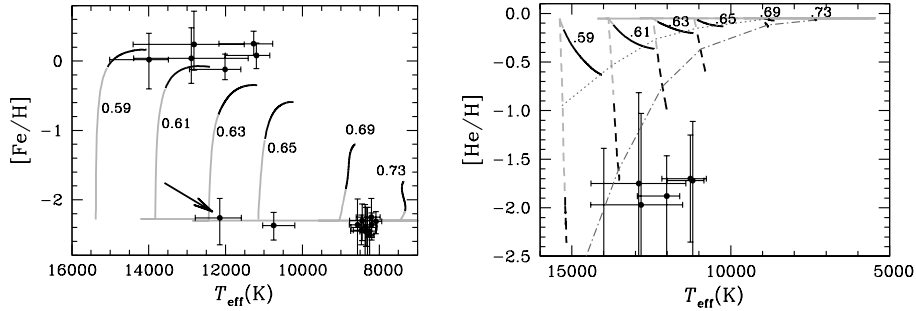


Figure 2. *Left panel*, concentration of surface $[\text{Fe}/\text{H}]$ expected in HB models compared to observations of Behr (2003) for M15. The continuous dark lines cover the interval from 5 to 30 Myr after zero age HB (ZAHB) for a number of models with a turbulence mixing the outer stellar region with $T < 100\,000$ K. The mass of each model is identified on the figure in M_{\odot} . The star marked with an arrow has $V \sin i \sim 16 \text{ km s}^{-1}$. All other stars with $T_{\text{eff}} > 11\,000$ K have $V \sin i < 8 \text{ km s}^{-1}$. *Right panel*, concentration of $[\text{He}/\text{H}]$ expected in two series of HB models compared to observations of Behr for M15. The continuous lines are defined similarly as for $[\text{Fe}/\text{H}]$ and were calculated with a turbulence that mixes the outer stellar region with $T < 100\,000$ K. The dashed lines were calculated with a turbulence that mixes the outer stellar region with $T < 30\,000$ K. The dotted line links models at 1 Myr after ZAHB while the dashed-dotted line links models at 5 Myr. One notes that the settling of He is some $30 \times$ faster if the star is stable up to $30\,000$ K.

many orders of magnitude. Given the size of the observed error bars of the He abundance, it may be premature to conclude that observations require separation within the outer $\log(\Delta m/M_*) \sim -7$. The right panel of Fig. 2 is however suggestive of the potential role of additional separation in atmospheric regions.

4. Pop I, AmFm and HgMn stars

The evolution code used above for HB stars had been used before by Richer *et al.* (2000) to model AmFm stars. In their model, the separation occurs relatively deep in the star, at $\log(\Delta m/M_*) \sim -5$ where Ca is in the Ne configuration. The concentration variations within a typical AmFm star may be seen in the right panel of Fig. 1. Results of the calculations were compared to observations for a number of stars. For instance in Fig. 19 of Richer *et al.* (2000) it is shown that there is reasonable agreement for 10 of the 11 chemical elements common to the observations and calculations for the Hyades star 68 Tau. In Fig. 18 of the same paper reasonable agreement is found for 12 out of 16 elements for Sirius.

While an alternate model for AmFm stars, assuming separation just below the H convection zone, is a possible alternative (Watson, 1971; Smith 1973;

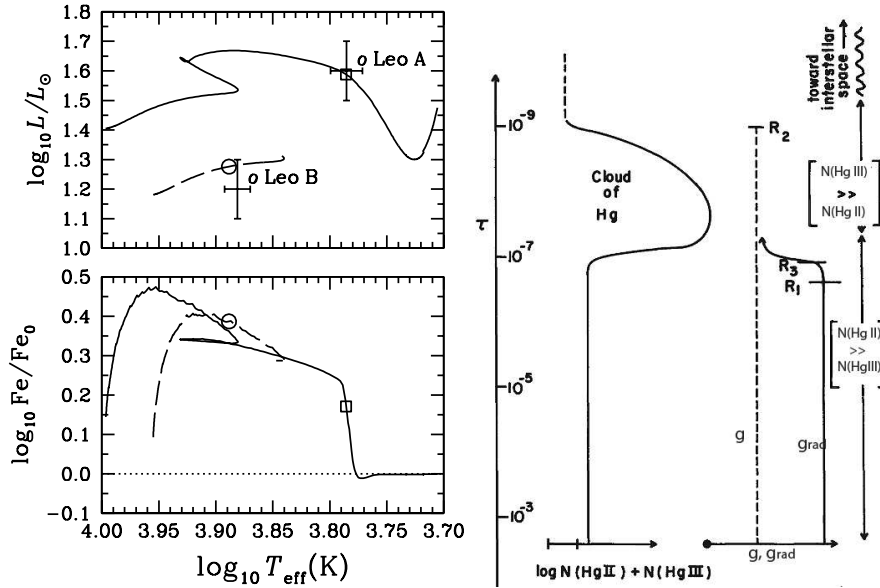


Figure 3. *Left panel*, in the upper part are shown, in the HR diagram, the observed positions indicated by crosses of the primary o Leo A and the secondary o Leo B as determined by Griffin (2002). One model is shown for the A component: $2.24 M_{\odot}$ (solid line) and one for the B component: $1.97 M_{\odot}$ (dashed line). When the computed primary has the observed T_{eff} (square), the $1.97 M_{\odot}$ secondary has the T_{eff} and L indicated by a circle, which is within the observed error bars. In the bottom part is shown the surface Fe abundance divided by the original value. *Right panel*, schematic description of an upper atmosphere assumed stable enough for separation to be important, from Michaud *et al.* (1974) In this example, Hg is pushed from the stellar interior by $g_{\text{rad}}(\text{Hg})$ to the point where $g_{\text{rad}} \sim g$. The reduction of the g_{rad} as τ decreases is caused by its progressive ionization into Hg III where it has fewer lines in the outgoing radiation flux than Hg II. Mercury accumulates there and forms a cloud.

Michaud *et al.*, 1983 a; Alecian, 1996), a strong argument for the Richer *et al.* (2000) model is offered by the observations of the system o Leo whose primary and secondary are both observed to be AmFm stars. The M , L and T_{eff} are relatively well constrained by the observations. The A component is observed to be unusually cool for an AmFm star. As may be seen in the upper left hand panel of Fig. 3, the A component is just about to become a red giant and is in a very rapid evolutionary stage. The presence in a binary system confirms its position in the HR diagram and the rapid evolutionary stage it is in. In the lower left hand panel, it is seen that the Fe concentration marks the AmFm character for both components even though the primary is in an advanced subgiant state. It is just

about to lose this Fe overabundance, however. A model with only superficial abundance anomalies on the main–sequence would not maintain them to the evolutionary stage of *o* Leo A. That the outer 10^{-5} of the stellar mass have modified concentrations in the Richer *et al.* (2000) model explains why such a subgiant can keep the AmFm characteristics.

In the right hand panel of Fig. 3 is found a schematic description of a HgMn atmosphere which is expected to have no outer convection zone. Clouds of various species are expected to form and can modify the concentration variations that come from the interior. This relatively simple model was found to explain many abundance anomalies observed on HgMn stars. For instance, Borsenberger *et al.* (1979) reproduced reasonably well the Heacox (1979) observations of Sr. Jomaron *et al.* (1999) measured Mn surface abundances in agreement with the Alecian and Michaud (1981) calculations.

The most careful calculation yet done of g_{rad} in HgMn stars is probably that of Proffitt *et al.* (1999) for Hg. It included careful evaluation of momentum sharing between ions. It was however carried for a homogeneous Hg abundance in the atmosphere. They found that an overabundance by a factor of 10^4 of Hg can be supported by $g_{\text{rad}}(\text{Hg})$ instead of the observed 10^5 overabundance. This is not that bad an agreement taking into account that it is most likely that a cloud of Hg actually forms in the atmosphere and that this would modify the Hg supported in the atmospheric region. Their assumption of a completely mixed outer atmosphere would certainly not explain the Hg isotope anomalies observed on HgMn stars (Preston, 1971). Hg isotope anomalies seem to require separation in the outer atmosphere Michaud *et al.* (1974). The presence of isotope anomalies is probably the strongest argument in favor of separation going on in the atmosphere in addition to the bottom of the mixed zone, both in HgMn stars and the probably related HB stars.

5. Conclusion

Assuming the outer $\sim 10^{-7}$ of the mass of HB stars to be mixed one obtains, with complete evolutionary models from the zero age main–sequence, abundance anomalies corresponding to those observed in M15 (§3.2.2). Similar success has been obtained for AmFm stars (§4). However such an assumption is almost certainly an oversimplification. There are some indications of atmospheric effects in the underabundances of He. If the values quoted by Behr (2003) are not too affected by NLTE effects, larger underabundances of He are observed than expected in our model. Our model leads to underabundances of He but not nearly as large as the underabundances claimed by Behr. However, as mentioned in §4, there are additional separations going on in the atmospheric regions of HgMn stars to which HB stars are very closely related as originally suggested by Sargent and Searle (1967; 1968). The similarity in T_{eff} and $\log g$ with HgMn stars suggests that separation in the atmosphere may play a role in HB stars

also. Note from the right hand panel of Fig. 2 that the model with the thinnest mixed zone develops much smaller He abundances than the one with complete mixing of the outer $\sim 10^{-7}$ of the mass. Extensive g_{rad} calculations in HB star atmospheres such as those of Hui-Bon-Hoa *et al.* (2000) would be required in order to couple surface and interior concentration variations more precisely.

The calculations described in §3.2.2 explain most of the T_{eff} dependence of [Fe/H] seen in Fig. 2, but not all of it. A potential link between the observed anomalies and rotation in HB stars has been analyzed in Quievy *et al.* (2007). From Figure 1 of that paper, there seems to be little doubt that rotation plays a role; furthermore according to their calculations involving a parameter free meridional circulation model, rotation explains why stars with $T_{\text{eff}} < 11\,000$ K have normal Fe abundances and why one of the hotter stars in M15 (the one indicated by an arrow in the right hand panel of Fig. 2) does not have abundance anomalies. While atomic diffusion driven by g_{rad} appears to play the major role in explaining the anomalies, the slow rotation of the hotter HB stars appears to be important also. It remains to be explained why they rotate so slowly. Similarly it is not understood why the main-sequence equivalent, the HgMn stars, rotate as slowly as they do. In this case one may assume a small original rotation rate but it is not clear that one may extend that assumption to HB stars. The slow rotation of the HB stars with $T_{\text{eff}} > 11\,500$ K remains unexplained.

Finally mass loss may also play a role. As shown by Vick and Michaud (Vick, Michaud 2008), including mass loss in models for AmFm stars leads to approximately as good agreement with observations as obtained in models assuming turbulent mixing. Observational tests are suggested to distinguish between the two processes but current observations are not accurate enough to allow the elimination of one or the other model. It would be interesting to determine if mass loss could be as successful as turbulent mixing for HB stars also.

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