THE SHAPE OF THE RED GIANT BRANCH BUMP AS A DIAGNOSTIC OF PARTIAL MIXING PROCESSES IN LOW-MASS STARS

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ABSTRACT

We suggest the use of the shape of the red giant branch (RGB) bump in metal-rich globular clusters as a diagnostic of partial mixing processes between the base of the convective envelope and the H-burning shell. The bump located along the differential luminosity function of cluster RGB stars is a key observable to constrain the H-profile inside these structures. In fact, standard evolutionary models that account for complete mixing in the convective unstable layers and radiative equilibrium in the innermost regions do predict that the first dredge-up produces a very sharp H-discontinuity at the bottom of the convective region.

Interestingly enough, we found that both atomic diffusion and a moderate convective overshooting at the base of the convective region marginally affects the shape of the RGB bump in the differential luminosity function (LF). As a consequence, we performed several numerical experiments to estimate whether plausible assumptions concerning the smoothing of the H-discontinuity due to the possible occurrence of extra mixing below the convective boundary affect the shape of the RGB bump. We found that the difference between the shape of RGB bump predicted by standard and by smoothed models can be detected if the H-discontinuity is smoothed over an envelope region whose thickness is equal or larger than 0.5 pressure scale heights. Finally, we briefly discuss the comparison between theoretical predictions and empirical data in metal-rich, reddening-free galactic globular clusters (GGCs) to constrain the sharpness of the H-profile inside RGB stars.

Subject headings: globular clusters: general — stars: evolution — stars: interiors — stars: Population II

1. INTRODUCTION

One of the most intriguing features of GGCs is the occurrence of a local maximum in the distribution of RGB stars. It appears as a bump in the differential LF and as a change of slope in the cumulative LF. After the pioneering investigations by Thomas (1967) and Iben (1968), it is well known that this feature is due to the fact that during the RGB evolution, the H-burning shell crosses the sharp chemical discontinuity left over by the convective envelope at the base of the RGB during its maximum sinking (first dredge-up). The abrupt change in the hydrogen abundance affects the efficiency of the H-burning shell, since the stellar luminosity undergoes a temporary drop. Dating back to the first detection in the GGC 47 Tucanae (King, Da Costa, & Demarque 1985), the RGB bump has been the crossroad of several theoretical and observational investigations (e.g., Fusi-Pecci et al. 1990; Alongi et al. 1991; Bono & Castellani 1992; Alves & Sarajedini 1999; Ferraro et al. 1999; Zoccali et al. 1999; Bergbusch & Vandenber 2001, and references therein). The main reason for this effort is that the RGB bump is a key observable to investigate the chemical profile inside RGB structures, and a robust diagnostic of the maximum depth reached by the outer convection during the first dredge-up.

Until a few years ago, a quantitative comparison between theory and observation was hampered mainly by the size of available stellar samples along the RGB. This problem is particularly severe for the most metal-poor GGCs, since the RGB evolutionary timescales are shorter than in metal-rich ones. Moreover, the RGB bump in metal-poor clusters is located at brighter magnitudes, and therefore in an RGB region poorly populated when compared with metal-rich clusters. However, the Hubble Space Telescope (HST), with its superior imaging quality and spatial resolution, allowed us to firmly detect this feature in a sample of GGCs that covers a wide metallicity range (Zoccali et al. 1999).

This paper is the fifth in a series devoted to the RGB bump in GGCs. Cassisi & Salaris (1997) investigated the dependence of bump luminosity on the physical inputs adopted to construct stellar models. They showed that the difference in magnitude between the RGB bump and the horizontal branch (HB) at the RR Lyrae instability strip \( \Delta V_{\text{bumpHB}} \) predicted by their updated evolutionary models agree quite well with empirical estimates of GGCs, for which accurate spectroscopic measurements of cluster-heavy element abundances are available. This evidence was further strengthened by the finding that \( \Delta V_{\text{bumpHB}} \) is only marginally affected by atomic diffusion (Cassisi, Degl’Innocenti, & Salaris 1997). A thorough comparison between predicted and observed \( \Delta V_{\text{bumpHB}} \) values brought forth that theory and observation do agree at the level of \( \approx 0.1 \) mag (Zoccali et al. 1999). To assess on a more quantitative basis the accuracy of current evolutionary models,
Bono et al. (2001) compared the evolutionary lifetimes during the crossing of the H-discontinuity with the star counts across the RGB bump. It turned out that theory is in very good agreement with observation over a wide range of metallicities. Only a few clusters were at odds with theoretical predictions, and 47 Tuc is one of them.

These investigations support the following evidence: (1) The maximum depth reached by the convective envelope at the base of the RGB, whose diagnostic is the $\Delta V_{\text{bump}}^{\text{HB}}$ parameter, is correctly predicted by stellar models. However, the parameter $\Delta V_{\text{bump}}^{\text{HB}}$ relies on the distances provided by HB models. As a consequence, the agreement between theory and observation relies heavily upon the adopted HB distance scale as well as on GGC metallicity scales (Rutledge, Hesser, & Stetson 1997; Zoccali & Piotto 2000; Bergbusch & Vandenberg 2001); and (2) The extent of H-discontinuity left over by the convective envelope, whose diagnostic is the star count across the RGB bump, depends neither on the distance scale nor on the metallicity scale, and it is correctly predicted by theory (Bono et al. 2001).

The main aim of this investigation is to study in detail how the sharpness of H-discontinuity affects the RGB bump. In particular, we are interested in estimating how this jump in the chemical composition affects the shape of the bump in the differential LF. The reason for such an investigation is twofold: (1) Current theoretical models do not firmly predict the efficiency and extent of all possible mixing processes occurring in stellar interiors as well as the occurrence of any partial mixing below the formal boundary of the convective region. It is worth mentioning that these physical mechanisms are no more purely speculative problems. In fact, Gratton et al. (2001) collected high-dispersion spectra for a sizable sample of stars in two GGCs with VLT/UVES and found that atomic diffusion presents a very low efficiency when moving from MS to SGB stars (see also Thévenin et al. 2001). This empirical evidence, once confirmed by new data, can supply useful hints on the occurrence of extra mixing processes in the region located below the convective envelope; (2) The sharpness of H-discontinuity does affect the evolutionary timescales (Bono & Castellani 1992) of the H-burning shell during the crossing of the H-discontinuity with the star that can allow us to detect a change in the shape of the bump. Therefore, a change in the extent of the smoothing region causes a change in the shape that can be constrained on the basis of the comparison with empirical data in metal-rich GGCs.

In § 2 we briefly discuss the stellar models adopted in our investigation, while in § 3 we investigate how different assumptions about smoothing lengths affect the shape of the bump and the star counts across the bump. This analysis is performed using the Monte Carlo method. In § 3 we also discuss the observational requirements and the target that can allow us to detect a change in the shape of the bump. Conclusions and future developments are outlined in § 4.

2. STELLAR MODELS

The evolutionary code and input physics adopted in this investigation are the same as in Cassisi & Salaris (1997). Theoretical models were transformed into the observational plane by adopting the bolometric corrections and color-temperature relations provided by Castelli, Gratton, & Kurucz (1997a, 1997b). We have focused our attention on a chemical composition typical of metal-rich GGCs, namely $Y = 0.23$ and $Z = 0.006$. Note that if we account for an $\alpha$-enhancement of $[\alpha/Fe] = 0.4$, this metallicity implies $[\text{Fe}/H] = -0.8$, i.e., the metallicity at which the number of RGB stars is expected to be the largest among the sample of GGCs. The numerical experiments were also performed at fixed stellar mass $M/M_\odot = 1$ since along the RGB the value of the evolving mass is almost constant. However, our conclusions do not depend on the selected mass value.

We computed several series of evolutionary models, from the zero-age main sequence up to the RGB phases brighter than the bump region. These models were constructed by neglecting or by accounting for atomic diffusion, and for various overshooting efficiencies, namely $0.1-0.2 H_p$, where $H_p$ is the pressure scale height at the base of the convective envelope. According to Alongi et al. (1991), stellar models which include convective overshooting were constructed by assuming instantaneous mixing in the overshooting region. These numerical experiments were performed to estimate whether these two physical mechanisms affect the sharpness of the H-profile. Interestingly enough, we found that in all these models the H-discontinuity is sharp, and the shape of the bump in the differential LF is the same as in standard models. This finding suggests that any detection of a peculiar shape in a cluster RGB bump is almost certainly caused by a smoothing of the H-discontinuity.

As a consequence, we performed the experiments on our standard models, i.e., the evolutionary models that neglect both atomic diffusion and convective overshooting, and at the base of the RGB we artificially modified, according to Bono & Castellani (1992), the abundance profiles below the point of maximum extent of the convective envelope. Then we evolved the new fictitious models well above the bump region. We have taken into account smoothing lengths of $0.1 H_p$, $0.2 H_p$, $0.5 H_p$, and $0.75 H_p$, where $H_p$ is the local pressure scale height at H-discontinuity. For the sake of simplicity, the chemical profiles in the smoothing region have been assumed to be linear, and the envelope abundances have been modified in such a way that the sum of element abundances by mass within the structure is perfectly conserved. Current smoothing lengths have been selected to fulfill two requirements: (1) To avoid a large shift in the luminosity of the bump along the LF. In fact, predicted and observed $\Delta V_{\text{bump}}^{\text{HB}}$ are, within current observational and theoretical uncertainties, in satisfactory agreement; and (2) To introduce a slight change in the sharpness of the H-discontinuity. In fact, the hydrogen distributed in the smoothed region has to be taken from the chemically homogeneous region located above the H-discontinuity. However, substantial changes in the chemical composition (mainly the hydrogen abundance) of this region cause a sizable variation in the star counts across the bump. Once again, current theoretical predictions seem to agree quite well with empirical estimates (Bono et al. 2001).

Figure 1 shows the hydrogen profile (H-abundance per unit mass) around the lower edge of the convective region at its maximum extent. The dashed line shows the canonical profile and presents a sharp H-discontinuity, while the solid line shows the H-profile after a linear smoothing of $0.5 H_p$ has been applied. The H abundance in the envelope attains quite similar values in the two cases, and indeed the difference is smaller than 0.001. This means that the jump in the H abundance between the envelope and the interior is very
similar, but in the nonstandard models the H-discontinuity has been smoothed over a thicker region when compared with the standard one.

3. THE EFFECT OF H-DISCONTINUITY ON THE SHAPE OF THE BUMP

To study in more detail the effect of the sharpness in the H-discontinuity on the shape of the RGB bump, we computed RGB luminosity functions of current stellar models. Figure 2 shows the LF of the RGB region located across the bump for our standard models; i.e., $M/M_\odot = 1$, $Z = 0.006$, and $Y = 0.23$, constructed by neglecting both atomic diffusion and convective overshooting.

The LF has been computed using the Monte Carlo method, the number of objects at a given luminosity being proportional to the local evolutionary timescale. We have used an extremely large number of objects to avoid spurious statistical fluctuations in a given luminosity bin. The bin size of the LF plotted in Figure 2 is 0.02 mag. It is worth mentioning that the intrinsic shape of the bump is asymmetric and presents a well-defined peak at its brightest end. Note that both the atomic diffusion and the convective overshooting below the formal boundary of the convective envelope do not change the shape of the bump, since in these models the H-discontinuity is as sharp as in standard models.

According to Bono et al. (2001), we define the parameter $R_{\text{bump}}$ as the number of stars located within $\pm 0.4$ mag above and below the luminosity peak of the bump, normalized to the number of RGB stars in the region between $+0.5$ and $+1.5$ mag below the peak of the bump. The standard models supply $R_{\text{bump}} = 0.527$, while models constructed by accounting for atomic diffusion, convective overshooting, or smoothed hydrogen profiles have values within 0.05 of the standard one. This difference is quite negligible, since it is smaller than the typical observational error bar (see Bono et al. 2001). On the other hand, the luminosity peak of the bump shifts by $\sim 0.07$ mag in the models that account for atomic diffusion (see also Cassisi, Degl'Ippocenti & Salaris 1997), while for the models that include convective overshooting, the brightness changes according to the derivative $\sim 0.8$ mag/$H_p$. At the same time, we found that an increase of 0.1 $H_p$ in the smoothing length causes (in the nonstandard models) a shift of $\sim 0.025$ mag in the position of the bump. Figure 3 shows the effect of smoothing on the shape of the bump. The dotted line refers to the standard LF, while the solid lines display the LFs of smoothed models. They have been plotted by shifting the brightest boundary of nonstandard bumps over the standard one. Different LFs are normalized to the same number of stars above the bump where the hydrogen profile is the same in all models.

The change in the shape of the bump as a function of smoothing length is quite evident. In particular, the bump becomes more centrally peaked and more symmetric for an increase in the thickness of the smoothing region. For smoothing lengths equal to or larger than $0.5 H_p$, the shape of the bump is substantially different than for standard models. According to the numerical experiments we already performed, such an effect cannot be produced by atomic diffusion or by convective overshooting. The reason for the difference in the shape of the bump is outlined in Figure 4.

\footnote{The $R_{\text{bump}}$ value of smoothed models is similar to the standard one, since the current smoothing length was chosen to avoid a substantial change in the jump of the H-profile.}
Fig. 3.—Comparison between the differential LF of our standard models (dotted line) and the LFs of the models constructed by artificially smoothing H-discontinuity over a region of 0.1 $H_p$, 0.2 $H_p$, 0.5 $H_p$, and 0.75 $H_p$ (solid lines). The LFs of smoothed models have been shifted in luminosity to match the bright edge of the bump of standard models.

This figure shows the evolution in the color-magnitude diagram (CMD) of our standard models and of the models with the H-discontinuity smoothed over a region of 0.5 $H_p$. A glance at the data plotted in this figure clearly shows that the bump region narrows in the latter case, and this change causes a narrowing of the bump in the differential LF as well.

The physical explanation of this behavior has to be related to the abrupt change of the mean molecular weight, $\mu$, in the region across the chemical discontinuity left over by the outer convection during the first dredge-up, and to the strong dependence of the H-burning efficiency on $\mu$. Standard models show a sharp change in the mean molecular weight at chemical discontinuity; this feature strongly affects H-burning efficiency, and in turn, stellar surface luminosity. In stellar models whose H-discontinuity has been smoothed, the sharpness of the $\mu$ variation is anti-correlated with the thickness of the smoothing region; as a consequence, the change of the H-burning efficiency is significantly lower in smoothed models than in canonical ones.

The top panel of Figure 5 shows the H-burning luminosity produced via the CNO cycle as a function of time. Data plotted in this figure disclose that the luminosity drop taking place during the crossing of the H-discontinuity is clearly correlated with smoothing length.
Smoothing of the H-discontinuity affects not only $\mu$, but also the opacity profile within the structure. To test the hypothesis that the change of opacity may play a role in causing the luminosity drop at the bump location, we performed the following test. We constructed a fictitious model in which the opacity in the region just below the H-discontinuity has been computed by adopting the same chemical composition of the region located above the H-discontinuity. Data plotted in the bottom panel of Figure 5 clearly show that the change in the opacity profile caused by variation in the chemical stratification has a negligible effect on the RGB bump. Therefore, it is the change of $\mu$ which determines the shape of bump region.

At the same time, we have to account for the difference in evolutionary timescales, since the number of stars in a given magnitude bin is proportional to this quantity. From top to bottom, the panels in Figure 6 show, for the two models plotted in Figure 4, the logarithm of stellar counts along the three branches of the bump region as a function of the $V$ magnitude. The data for nonstandard models were shifted in brightness as in Figure 3. The arrows mark the direction during these evolutionary phases, i.e., the change in surface luminosity. Figure 6a shows the star counts before the temporary decrease in luminosity, while Figure 6b shows the star counts during the subsequent decrease in luminosity. The evolutionary timescale of standard models at the bin where the luminosity does not increase is roughly a factor of 2 longer than in smoothed models, while it is systematically shorter during phases approaching this point and phases in which luminosity decreases. During this latter phase, standard models reach the secondary minimum in luminosity quite rapidly when compared with the smoothed models. In fact, the evolutionary timescale of smoothed models in the fainter luminosity bin is a factor of 3 longer than in standard models. Figure 6c shows the predicted stellar counts during the phases in which surface luminosity increases once again. The evolutionary timescale of standard models is essentially constant, while smoothed models evolve more rapidly until they approach the bright edge of the bump region.

In this section, we have discussed the difference in the LF between standard and smoothed models. We now wish to address the following question: Can this difference be detected in actual RGB bumps? To answer this question, we performed new Monte Carlo simulations by accounting for different sample sizes and observational errors. Figure 7 shows the same LFs plotted in Figure 2, but they were computed by adopting a bin size of 0.05 mag and a $1\sigma$ random photometric error by 0.025 mag. It is worth noticing that the accuracy of the photometric zero point is not relevant in this discussion. Data plotted in this figure suggest that smoothing lengths equal to or larger than 0.5 $H_p$ still affect the shape of the bump in such a way that the difference between standard and smoothed models can be detected. According to our simulations, to detect smoothing lengths equal to or larger than 0.5 $H_p$ in metal-rich clusters.
Figure 6.—Comparison between the differential LFs of standard models (dotted line) and of models whose H-discontinuity was smoothed out over a region of 0.5 $H_p$ (solid line). From top to bottom, the three panels refer to different evolutionary phases across the bump, namely (a) from the faint edge of the bump to the secondary maximum, (b) from the secondary maximum to the secondary minimum, and (c) from the secondary minimum to the bright edge of the bump. Arrows mark the evolutionary direction, i.e., the change in surface luminosity along the three branches.

Figure 7.—Same as in Fig. 3, but differential LF was constructed by adopting a bin size of 0.05 mag and 1σ random photometric errors of 0.025 mag.
The dashed line displays the LF of the model with $Z$ models constructed by adopting compositions. The dotted and the solid line show the LFs of standard mixing processes induced by rotation. However, current $H$-discontinuity in the envelope of RGB stars, stabilizes the occurrence of gradients in the molecular weight, such as (Erstein 1998, and references therein) suggest that the 1957) and spectroscopic data (Charbonnel, Brown, & Wallerstein 1998, et al. 2001). The occurrence of(The venin from satisfactory et al. 2001). The occurrence of(The venin suggested that rotation-induced mixing occurs above the RGB bump (Sweigart & Mengel 1995). However, even by accounting for this extra mixing process, the Li abundance in Population II stars, it has been suggested that rotation-induced mixing occurs above the RGB bump (Sweigart & Mengel 1995; Charbonnel 1995). However, even by accounting for this extra mixing process, the agreement between empirical data and theory is far from satisfactory (Thévenin et al. 2001). The occurrence of mixing below the bottom of the convective region has been generally neglected, since theoretical predictions (Mestel 1957) and spectroscopic data (Charbonnel, Brown, & Wallerstein 1998, and references therein) suggest that the occurrence of gradients in the molecular weight, such as $H$-discontinuity in the envelope of RGB stars, stabilizes the mixing processes induced by rotation. However, current spectroscopic measurements support the evidence that RGB stars located across the bump present large Li abundances (Charbonnel & Balachandran 2000). This suggests that these stars underwent Li production immediately before or at the bump phase. The comparison between predicted and observed shape of RGB bumps can supply tight constraints on the sharpness of $H$-discontinuity, and in turn on the inhibiting effect of molecular weight barriers on extra mixing related either to rotation or to exotic phenomena.

We constructed several stellar models by assuming different smoothing lengths, and we found that for smoothings up to 0.75 $H_p$, current theoretical predictions concerning the difference in luminosity between the peak of RGB bump, the HB, $AV_{H_bump}$, and star counts across the bump region, $R_{bump}$, are still in satisfactory agreement with observations. However, as expected, a change in the $H$-abundance profile significantly affects the evolutionary timescales of the H-burning shell, and in turn the shape of the RGB bump along the LF. Interestingly enough, we found that it is possible to constrain the sharpness of the $H$-discontinuity at the base of the envelope of RGB stars by comparing predicted and empirical bump shapes of differential LFs in metal-rich GGCs.

In this context, it is worth mentioning that this finding is far from being a speculative issue. In fact, the new Advanced Camera for Surveys (ACS, Clampin et al. 2000) on board $HST$ will supply, thanks to its wide field of view ($202 \times 202$ arcsec$^2$) and homogeneous spatial resolution (0.05 per pixel), a complete census of RGB stars over a substantial fraction of GGC’s innermost regions. In particular, for clusters characterized by relatively high central densities, the ACS can measure at the star-by-star level the bulk of cluster RGB stars. As a consequence, the detection of the shape of the RGB bump among massive metal-rich clusters will become feasible in the near future. To constrain on a quantitative basis the empirical requirements necessary to supply an accurate detection of the shape of the bump, we performed several Monte Carlo experiments according to current theoretical predictions. We found that a robust detection requires a minimum sample of more than $\sim 120$ RGB stars within $\pm 0.2$ mag of the peak of the bump, the use of a bin size up to 0.06 mag in the LF, as well as random photometric errors smaller than 0.03 mag. Fortunately, several metal-rich GGCs and the new scientific capabilities of $HST$ allow us to cope with this challenging and intriguing project.

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