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STELLAR ENVELOPE CONVECTION CALIBRATED BY RADIATION HYDRODYNAMICS SIMULATIONS: INFLUENCE ON GLOBULAR CLUSTER ISOCHRONES

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ABSTRACT

One of the largest sources of uncertainty in the computation of globular cluster isochrones and hence in the age determination of globular clusters is the lack of a rigorous description of convection. Therefore, we calibrated the superadiabatic temperature gradient in the envelope of metal-poor low-mass stars according to the results from a new grid of two-dimensional hydrodynamical models, which cover the main sequence and the lower red giant branch of globular cluster stars. In practice, we still use for computing the evolutionary stellar models the traditional mixing-length formalism, but we fix the mixing-length parameter α in order to reproduce the run of the entropy of the deeper adiabatic region of the stellar envelopes with effective temperature and gravity as obtained from the hydrodynamical models. The detailed behavior of the calibrated α depends in a nontrivial way on the effective temperature, gravity, and metallicity of the star. Nevertheless, the resulting isochrones for the relevant age range of Galactic globular clusters have only small differences with respect to isochrones computed adopting a constant solar calibrated value of the mixing length. Accordingly, the age of globular clusters is reduced by 0.2 Gyr at most.

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

1. INTRODUCTION

One of the most important unsolved problems of stellar evolution is the determination of the temperature gradient in the superadiabatic regions at the top of the convective envelopes of cool stars, which strongly affects the effective temperature ($T_{\rm eff}$) of these objects. The mixing-length theory (MLT; Böhm-Vitense 1958) is widely used for deriving this gradient. It contains a number of free parameters, among them α, the ratio of the mixing length to the pressure scale height, which provides the scale length of the convection. There are different versions of the MLT, each one assuming different values for these parameters. As demonstrated by Pedersen, Vandenberg, & Irwin (1990), the $T_{\rm eff}$ values obtained from the different formalisms are equivalent, provided that a suitable value of α is selected (see also Gough & Weiss 1976). This means that the MLT results concerning stellar structure models depend only on one free parameter, namely α, and its absolute value depends on the selected MLT formalism. Once the formalism is fixed, α is usually calibrated by reproducing the solar $T_{\rm eff}$, and this solar-calibrated α is then used for computing models of stars very different from the Sun (e.g., metal-poor red giant branch and main-sequence stars of various masses). However, in principle there is no compelling reason that α should be the same for the Sun and different kinds of stars.

More recently, Canuto & Mazzitelli (1991, hereafter CM) proposed a new formalism for the treatment of the superadiabatic convection; they took into account the full turbulent energy spectrum and set the convective scale length equal to the geometrical depth from the top of the convective region. Comparisons between MLT (solar-calibrated α) and CM stellar models show that isochrones computed with the CM formalism cannot be reproduced by the MLT with any constant value of α (Mazzitelli, D'Antona, & Caloi 1995).

The problem of determining accurate effective temperatures for cool stars affects the globular cluster (GC) age determination and, in turn, the estimated age of the universe. Large variations of α alter the derived stellar $T_{\rm eff}$ and colors and change the shape of GC isochrones; as demonstrated by Chaboyer (1995; see also Chaboyer et al. 1998), the change of the isochrone shape can even modify the luminosity of the turn off (TO; the bluest point along a given isochrone). Moreover, when comparing CM and MLT isochrones, one finds that for the most metal-poor isochrones in the relevant range of ages of the metal-poor galactic GCs, the TO luminosity obtained from the CM isochrones differs appreciably from the case of the MLT (Mazzitelli et al. 1995). Since the TO brightness is the main age indicator for GCs, uncertainties in the convection treatment can affect the estimated GC ages (by ≈1 Gyr or even more).

In principle, one could try to constrain the convective efficiency by comparing theoretical isochrones with regions of the observed color-magnitude diagrams of GCs whose colors are unaffected by the cluster age, but the large uncertainties that still exist in the color transformations (see, e.g., Weiss & Salaris 1999) do not permit one to safely follow this approach. An empirical constraint is given by the $T_{\rm eff}$ of the upper red giant branches of a sample of GCs as derived by Frogel, Persson, & Cohen (1981). MLT models computed with a solar-calibrated α (see, e.g., Vandenberg, Bolte, & Stetson 1996; Salaris & Weiss 1998) appear to be in agreement with these empirical data, even if a precise error bar on the α value calibrated in this way is hard to establish, which is probably in the range ±0.1–0.3 (see Vandenberg et al. 1996 and references therein). However, this "empirical" calibration in principle does not constrain the convection along the main sequence and the lower red giant branch of GCs.

Both the MLT and CM formalisms assume a simplified, time-independent, one-dimensional, local treatment of a typically nonstationary, multidimensional, and nonlocal phenomenon, which the stellar convection actually is. The final solution to the problem of the superadiabatic convection in stellar envelopes has to come from the computation of realistic multidimensional radiation hydrodynamics (RHD) simulations covering the range of effective temperatures, gravities, and compositions typical of stars with convective envelopes. First attempts to include in stellar models the results from rather crude two-dimensional (2D) and three-dimensional (3D) hydrodynamical simulations date back to the works by Deupree & Varner (1980) and Lydon et al. (1992, 1993a, 1993b).

In this Letter, we discuss the first application to the computation of GC isochrones of new results obtained from a grid of detailed 2D RHD models including realistic microphysics and a detailed treatment of the radiative transport. A further important feature of these models is that they span a wide range in metallicity ([M/H] = -2.0 to 0.0; here we adopt the usual spectroscopic notation [M/H] = $\log{(M/H)}_{\rm star} - \log{(M/H)}_{\odot}$, where M is the global metal abundance) and cover the main sequence (MS) and lower red giant branch (RGB) region of GC color-magnitude diagrams.

2. HYDRODYNAMICAL MODELS AND CALIBRATION OF THE EFFICIENCY OF CONVECTION

The full grid of RHD models is described in detail elsewhere (Ludwig, Freytag, & Steffen 1999; Freytag, Ludwig, & Steffen 1999a, 1999b), and a comprehensive discussion about the numerical and physical assumptions of the RHD simulations can be found in Ludwig, Jordan, & Steffen (1994). Here we just recall the main features of the models. Each 2D model describes the atmosphere and upper layers of a star with a convective envelope. It is obtained by solving the time-dependent, nonlinear equations of hydrodynamics for a stratified compressible fluid. The calculations take into account a detailed treatment of the equation of state and of the multidimensional, nonlocal, radiative transfer (for more details, see Ludwig et al. 1994). Similar to classical model atmosphere calculations, the hydrodynamical models are fully determined by specifying $T_{\rm eff}$, acceleration of gravity g, and chemical composition, and they lie in the range 4300 K $\leq T_{\rm eff} \leq$ 7100 K, $2.54 \leq \log{(g)} \leq 4.74$, $-2.0 \leq$ [M/H] ≤ 0.0.

From this grid of models, one can extract the entropy of the deeper, adiabatic convective layers ($s_{\rm env}$) as a function of $T_{\rm eff}$, g, and [M/H] (see Ludwig et al. 1999; Freytag et al. 1999a, 1999b). Once this relation is implemented in a stellar evolution code, it completely fixes the $T_{\rm eff}$ of the star as determined from the solution of the stellar structure equations.

A way for implementing easily this dependence of $s_{\rm env}$ on $T_{\rm eff}$ and g into an evolutionary code makes use of the MLT formalism. As explained in detail by Ludwig et al. (1999), for each fixed metallicity one can compute a grid of hydrostatic one-dimensional stellar envelope models based on the MLT, covering the same range of g and $T_{\rm eff}$ spanned by the RHD computations and using the same input physics. By employing as surface boundary condition the $T(\tau)$ relation derived from the hydrodynamical models, one can calibrate an effective α ($\alpha_{\rm eff}$) that is able to reproduce the $s_{\rm env}$-$T_{\rm eff}$ relation obtained from the RHD computations. In this way one can derive a function $\alpha_{\rm eff} = f(T_{\rm eff}, g)$ at each metallicity that is easy to use for computing stellar evolutionary models. The estimated error on the

values of $\alpha_{\rm eff}$ derived by means of this procedure is equal to ± 0.05 (Ludwig et al. 1999).

Ludwig et al. (1999) discuss the comparison of their RHD model for the solar envelope with the results from helioseismology. They show that the entropy at the bottom of the superadiabatic region as derived from helioseismology would imply a value of $\alpha_{\rm eff}$ for the Sun slightly higher, by $\approx 0.10 \pm 0.05$, than the value deduced from their RHD models. This small discrepancy is explained by comparing their result with the outcome of similar 3D simulations and by the examination of the opacities used in their models. For the Sun, the 3D models predict an increase of α by $\approx 0.07 \pm 0.02$ with respect to the 2D ones, and the ATLAS6 opacities (Kurucz 1979) used in the models do not consider the contribution of the molecules. The effect of including this contribution to the opacity would further change α by ≈ 0.1. The combination of these two effects explains the small discrepancy between the adopted solar RHD model and the results from helioseismology. Another important result derived from the RHD models is that the effect of the envelope He abundance on the derived $\alpha_{\rm eff}$ values is basically negligible.

The calibration of $\alpha_{\rm eff}$ for metal-poor stars has been performed by Freytag et al. (1999a, 1999b), and we have used their results for computing isochrones with typical GC metallicities [M/H] = -2.0 and -1.0 (scaled solar metal distribution), $Y = 0.23$, and age t ranging from 9 to 14 Gyr, using the code described in Salaris, Degl'Innocenti, & Weiss (1997). We have employed the same $T(\tau)$ relation and the same MLT formalism (Böhm-Vitense 1958) used in the calibration of $\alpha_{\rm eff}$.

We have computed a first set of isochrones using the ATLAS6 low-temperature opacities. The only source of possible inconsistencies with the RHD models was in this case the equation of state employed in the evolutionary calculations (see Salaris et al. 1997), which is not the same as in the RHD computations. Nevertheless, we have verified that it does not modify appreciably $\alpha_{\rm eff}$ as derived from the RHD calibration. For the sake of comparison, we have computed isochrones for the same age and metallicities but using a constant, solar-calibrated value of α ($\alpha_{\odot}$). Since the ATLAS6 data do not include the contribution of the molecules to the opacity of the stellar matter, we have repeated the same evolutionary computations previously described (with $\alpha_{\rm eff}$ and $\alpha_{\odot}$), using this time the updated Alexander & Ferguson (1994) low-temperature opacities, which include the molecular contribution. When using these opacity data, we found a small effect only on the zero point of the $\alpha_{\rm eff} = f(T_{\rm eff}, g)$ relation. To fix the ideas, the solar calibration with the evolutionary code yields in this case $\alpha = 1.69$, while from the RHD models one gets $\alpha = 1.59$ for the Sun, which means a deviation by a factor of 1.06. This small correction factor (which makes consistent the entropy of the adiabatic layers as derived from RHD models and from helioseismology) for the $\alpha_{\rm eff} = f(T_{\rm eff}, g)$ relation has therefore been taken into account in the evolutionary calculations.

At this point, we have verified that the differences among isochrones computed with $\alpha_{\rm eff}$ and $\alpha_{\odot}$ are exactly the same in the case of models computed with ATLAS6 or Alexander & Ferguson (1994) opacities. Since the latter data are a more realistic evaluation of the opacity of stellar matter, in the following section we will discuss the isochrones computed using the Alexander & Ferguson (1994) opacities.

Before concluding this section, we would like to stress the fact that the derived calibration of $\alpha_{\rm eff}$ is *only intended to re-*
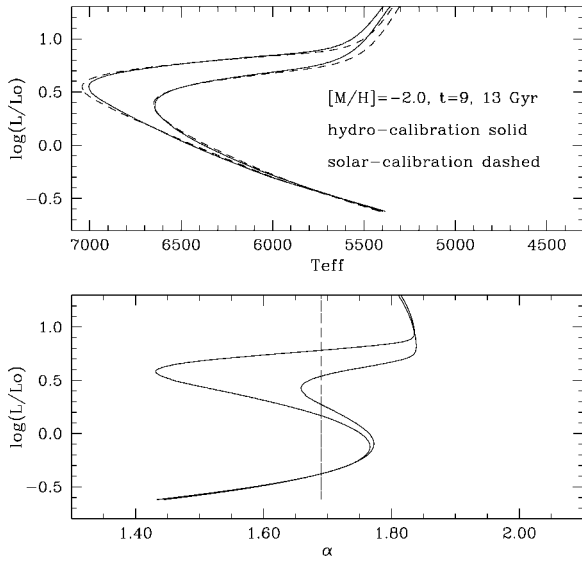
FIG. 1.—*Top:* Isochrones in the $T_{\rm eff}$-log $(L/L_\odot)$ diagram for [M/H] = −2.0. Two isochrones (t = 9, 13 Gyr) computed with $\alpha_{\rm eff}$ (*solid lines*) are compared to the corresponding isochrones computed with a constant $\alpha_\odot$ (*dashed lines*). *Bottom:* Values of $\alpha_{\rm eff}$ along the hydrodynamic calibrated isochrones; the vertical line represents the constant $\alpha_\odot$ of the standard isochrones.

produce the function $s_{\rm env}(T_{\rm eff}, g)$ of the RHD models. The detailed temperature profile and convective velocities of the superadiabatic layers are not represented adequately by the MLT with $\alpha_{\rm eff}$, but our main concern here is only the determination of reliable effective temperatures for cool stars.

3. RESULTS AND DISCUSSION

Representative isochrones (9 and 13 Gyr) for the two considered metallicities computed with $\alpha_{\rm eff}$ and $\alpha_\odot$ are displayed in Figures 1 and 2 (*top panels*). The most striking feature is the close resemblance between the two sets of isochrones. The MS loci are coincident, and the $T_{\rm eff}$ values of the TO points are very similar (notice the linear scale for the $T_{\rm eff}$ axis), the biggest difference being equal to ≈45 K for the 9 Gyr most metal-poor isochrone (an age possibly too young for the metal-poor galactic GC population; see, e.g., Salaris & Weiss 1998). Along the RGB the isochrones computed by using $\alpha_{\rm eff}$ are systematically hotter by only ≈50 K for [M/H] = −1.0 and ≈40 K for [M/H] = −2.0. To explain this behavior, it is useful to study the run of $\alpha_{\rm eff}$ with respect to log $(L/L_\odot)$ along the same isochrones, as shown in Figures 1 and 2 (*bottom panels*).

The differences between $\alpha_{\rm eff}$ and $\alpha_\odot$ along the lower MS are hardly relevant, since the $T_{\rm eff}$ of these stars is insensitive to the choice of α (the entropy jump from the photosphere to the deep adiabatically stratified layers is small anyway), while around the TO they depend on the age of the isochrones. In general, in the youngest, most metal-poor isochrones, $\alpha_{\rm eff}$ shows the largest difference with respect to $\alpha_\odot$, but since stars in these phases are quite hot ($T_{\rm eff} \approx 7000$ K) and their convection zones are relatively shallow, the sensitivity of $T_{\rm eff}$ to α is not very large. Along the RGB, where the $T_{\rm eff}$ of stellar models is most sensitive to α because of deeper superadiabatic regions, $\alpha_{\rm eff}$ is systematically higher than $\alpha_\odot$ by 0.10–0.15 for both metallicities. This difference causes a systematic shift by ≈50 K toward higher $T_{\rm eff}$ with respect to the case of $\alpha_\odot$, a quantity marginally significant since the error by ±0.05 on $\alpha_{\rm eff}$ translates
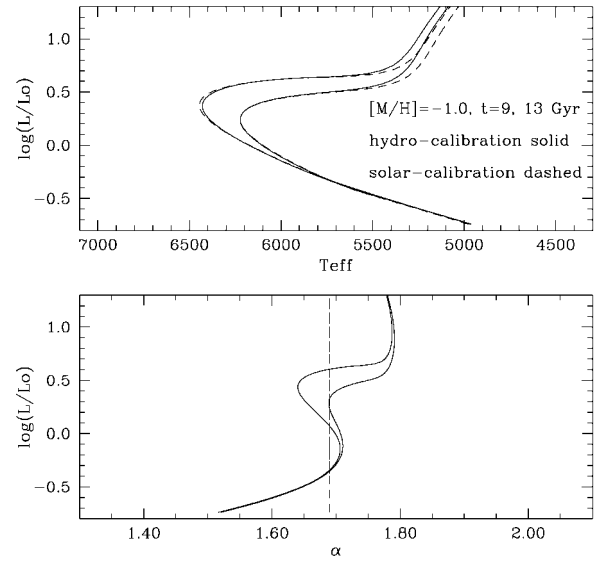

FIG. 2.—As in Fig. 1, but for [M/H] = −1.0.

into an error by ≈±15–20 K on the RGB $T_{\rm eff}$). Qualitatively, the behavior of isochrones computed using $\alpha_{\rm eff}$ looks similar, for certain features, to the results of the CM formalism; we are referring here to the fact that the TO is cooler (but only for the youngest, more metal-poor isochrones) than for the models computed with $\alpha_\odot$. But the differences that we find are smaller than the predictions of the CM formalism. Moreover, the RGB location in the $\alpha_{\rm eff}$ isochrones is only slightly hotter than in the $\alpha_\odot$ ones, while in the case of CM models the RGB is cooler at low metallicity and progressively hotter for increasing metallicities.

At this point, let us turn our attention to the GC age indicators that one can extract from the isochrones. The TO brightness is the most solid one; once the distance is fixed (e.g., from the horizontal branch luminosity or by means of the subdwarf fitting technique), the comparison between theoretical and observed TO gives directly the cluster age. The TO color is also a possible age indicator once the reddening is known, but the present uncertainties on the color transformations do not favor this method for deriving absolute ages, even if the isochrone $T_{\rm eff}$ and the GC reddenings are determined with high accuracy. A third possibility is to use the reddening– and distance modulus–independent quantity $\Delta(B-V)$, that is the difference in $(B-V)$ between the TO and the base of the RGB, as defined by Vandenberg, Bolte, & Stetson (1990). Again, the uncertainties on the color transformations prevent one from using the absolute value of $\Delta(B-V)$ for deriving absolute GC ages, but the differential use of this quantity is a solid and widely employed indicator of age differences (see, e.g., Vandenberg et al. 1990; Salaris & Weiss 1997), and it is weakly dependent on [M/H].

In Figure 3 (*top and middle*), we compare the TO position (brightness and color) in the age range 9–14 Gyr for the two sets of isochrones with $\alpha_{\rm eff}$ and $\alpha_\odot$. We have transformed the isochrones to the observational $V-(B-V)$ plane according to the colors and bolometric corrections used by Salaris & Weiss (1998), but the results of this comparison do not depend on the particular set of transformations used. As is evident from the figure, the age differences as derived from the TO brightness (or color) are basically negligible.
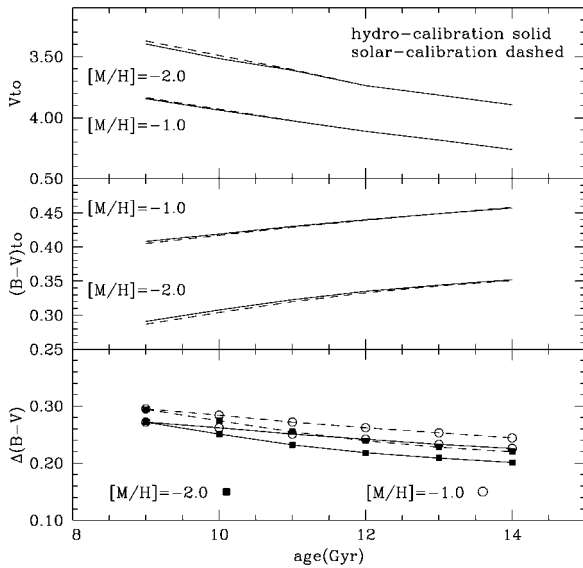
Fig. 3.—*Top:* M_v values for the TO of isochrones computed by using either $\alpha_{\rm eff}$ or $\alpha_{\odot}$, [M/H] $= -2.0$ and -1.0, and $t = 9$–14 Gyr. *Middle:* As in the top panel, but for the TO $(B-V)$ color. *Bottom:* The same, but for the quantity $\Delta(B-V)$.

In Figure 3 (*bottom*), we compare $\Delta(B-V)$ as a function of the age for both sets of isochrones. At each metallicity, the two curves corresponding to the two calibrations of the convection lie parallel for all of the relevant age range (the absolute values being different by only ≈ 0.02 mag). Therefore, the derivative $\delta[\Delta(B-V)]/\delta t$ [and the relative ages derived for the $\Delta(B-V)$] is not affected at all when $\alpha_{\rm eff}$ is used instead of $\alpha_{\odot}$.

In conclusion, the main results of this analysis show that the $T_{\rm eff}$ of GC isochrones computed employing the MLT formalism and $\alpha_{\odot}$ or the $\alpha_{\rm eff}$ calibration as derived from detailed RHD models are in good mutual agreement: the maximum deviations in the relevant age range for galactic GC amounts at most to a systematic shift by $\approx 50 \pm 20$ K along the RGB. As previ-

ously discussed, preliminary comparisons (Ludwig et al. 1999) between the adopted grid of 2D RHD models and a small sample of 3D ones show only a very small systematic shift of $\alpha_{\rm eff}$ as derived from the RHD models by ≈ 0.07, which does not affect our results appreciably.

The next necessary step for finally solving the problem of superadiabatic convection in stellar envelopes involves the computations of 3D model grids with up-to-date equation-of-state tables and frequency-dependent opacity tables to improve especially the photospheric temperature structure. Particularly the resolution of the numerical grid in the vertical direction should be improved to resolve the extremely sharp temperature jump at the bottom of the photosphere when the computations are extended to higher luminosities. A better coverage of the transition region from efficient to weak (radiation-dominated) convection at high effective temperatures would improve the base to judge between the MLT and the CM formalism. Nevertheless, the grid of 2D models that already exists indicates that in the $T_{\rm eff}$-log g-[M/H] region of interest for GC stars, there is no drastic change in the properties of the envelope convection. Accordingly, the use of the MLT with a constant solar-calibrated $\alpha_{\odot}$ leads only to insignificant errors of at most 0.2 Gyr in the derived ages of GCs.

It is important also to remark again that the structure of the superadiabatic convective regions is not suitably reproduced either by $\alpha_{\odot}$ or by $\alpha_{\rm eff}$ and that the complete results from RHD models have to be employed whenever a detailed description of the properties of these layers is needed (e.g., for astro- and helioseismology). In addition, the RHD models should be analyzed regarding the effects on the $T_{\rm eff}$ color transformations.

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