Astron. Astrophys. 344, 97–100 (1999)

ASTRONOMY AND ASTROPHYSICS

Microscopic diffusion and the calibration of globular cluster ages

V. Castellani[1] **and S. Degl'Innocenti**[1,2]

[1] Dipartimento di Fisica, Universitá di Pisa, Piazza Torricelli 2, I-56126 Pisa, Italy
[2] Istituto Nazionale di Fisica Nucleare, Sezione di Ferrara, Via Paradiso 12, I-44100 Ferrara, Italy

Received 22 October 1998 / Accepted 8 January 1999

Abstract. We discuss current uncertainties in the predicted magnitudes of Turn-Off (TO) and Zero Age Horizontal Branch (ZAHB) stars, as produced by uncertainties in the efficiency of element sedimentation in low mass, metal poor stars. One finds that for ages of the order of 10 Gyr the uncertainties in sedimentation affect the calibration of the TO luminosity in terms of cluster ages less than 1 Gyr, this uncertainty becoming however larger for larger cluster ages. The difference in magnitude between TO and ZAHB stars, ΔV(TO-HB), appears less affected by sedimentation, since the variation in the TO luminosity is partially balanced by a similar variation of ZAHB luminosities. However additional uncertainties in the theoretical ZAHB luminosity are discussed, showing that a conservative estimate of uncertainties in the ZAHB V magnitude gives an error of $+0.106/-0.047$ and an uncertainty in the calibration of ΔV(TO-HB) in terms of the cluster age of the same order of the uncertainty in the calibration of TO magnitudes.

Key words: stars: Population II – stars: horizontal-branch – stars: evolution

1. Introduction

Globular clusters are the oldest objects in the Galaxy, and their ages provide relevant information on the early phases of galactic evolution as well as a firm lower limit to the age of the universe. As well known, the "stellar clock" marking the cluster age is given by the absolute luminosity of the Turn-Off. Observational constraints on such a luminosity require however the knowledge of the cluster distance modulus and, thus, the adoption of suitable standard candles, which in general are found either in the main sequence(MS) or in the horizontal branch (HB) evolving structures. In the last case the age determination technique is the so called ΔV(TO-HB) method and it has the advantage of being independent of cluster reddening.

In the last years large efforts have been devoted to reconcile the evaluation of globular cluster ages with the age of the universe as given by the Hubble constant. Thanks to the progressive updating of the physics inputs several authors have presented new evaluations of globular cluster ages which appear now in agreement within the estimated uncertainties with the cosmological value (but see Pont et al. 1998). However, similar evolutionary results are affected by theoretical uncertainties which have to be taken into account. An excellent discussion about the uncertainties connected to several physics ingredients of stellar models has been presented by Chaboyer (1995).

More recently, helioseismological constraints have brought to light the evidence that diffusion of helium and heavy elements must be at work in the Sun, affecting, in turn, also the structures of both MS and HB stars (see, e.g., Castellani et al. 1997 and references therein). However, diffusion is not a simple mechanism, easy to be evaluated, and the range of efficiencies allowed by helioseismology is still relatively broad. Fiorentini et al. (1998) estimated for the Sun an uncertainty of the order of $\pm$30%. However, the uncertainty largely increases when passing from the Sun to stars with different masses and original chemical compositions, for which one has no seismological constrains. For these stars one can safely estimate that the efficiency of diffusion is probably known no better than a factor of two.

In this note we will discuss the uncertainties in the brightness of both the TO and the ZAHB stars, as due to the variation of the efficiency of diffusion within these limits. A discussion about further uncertainties in the ZAHB luminosity will close the paper.

2. Element diffusion and stellar models

To investigate the effect of a variation of the diffusion efficiency on the evolution of low mass, population II stars we followed the same approach used to test this efficiency in Solar Standard Models (Fiorentini et al. 1998), just multiplying by a constant factor the canonical diffusion velocities. Following such a procedure, we computed a suitable set of stellar models for the assumed composition Z=0.0002 and Y=0.23 with the physical inputs described in Cassisi et al. 1998a). Evolutionary results were finally used to produce cluster isochrones in the range of ages 8 to 18 Gyr. Luminosities have been translated into V magnitude according to model atmospheres by Castelli et al. (1997a,b).

Fig. 1 shows the V magnitude of the TO as a function of the cluster age in the no-diffusion case as compared with the case of standard diffusion and with diffusion velocities divided or

Send offprint requests to: S. Degl'Innocenti, (scilla@astr18pi.difi.unipi.it)

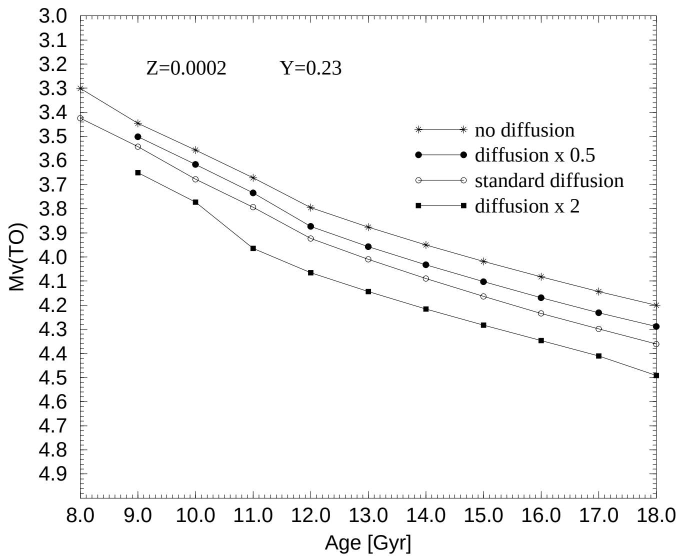

Fig. 1. Visual magnitude of the TO isochrones as a function of the age, for the various labeled assumptions about the efficiency of microscopic diffusion. Chemical composition as labeled. Visual magnitudes are from model atmospheres by Castelli et al. (1997 a,b) (see the discussion in Cassisi et al. 1998b).

Table 1. The mass of helium core at the He flash (M_c^{He}) and the surface helium abundance (Y_{HB}) for a 0.8 $M_\odot$ under the labeled assumptions about the efficiency of microscopic diffusion (see text). Chemical composition as labeled.

	M_c^{He} [$M_\odot$]	Y_{HB}
Z=0.0002 Y=0.23		
no diffusion	0.511	0.239
diffusion $\times$ 0.5	0.514	0.232
std. diffusion	0.515	0.226
diffusion $\times$ 2	0.519	0.214

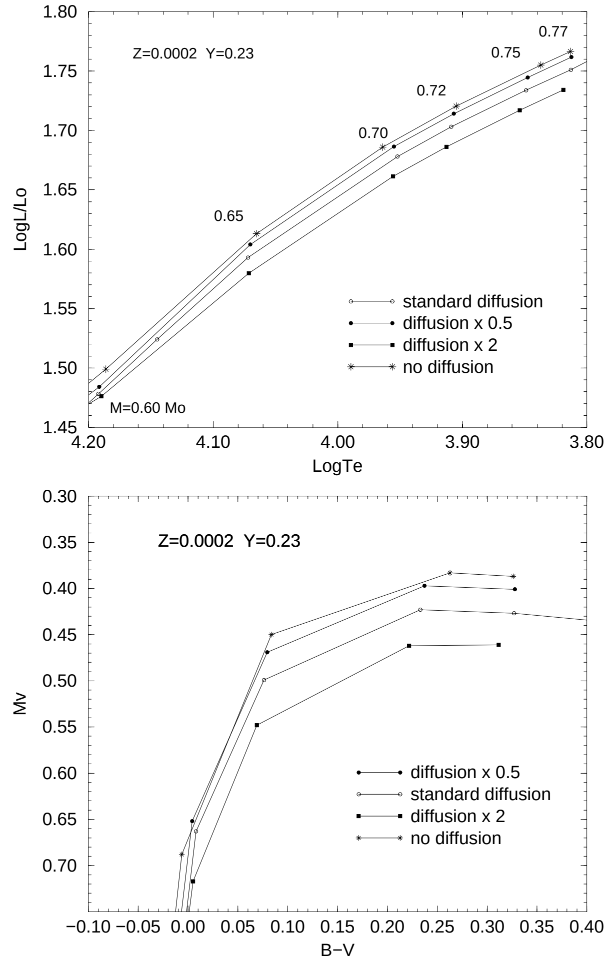

Fig. 2a and b. Zero Age Horizontal Branches in the theoretical (panel **a**) and observational (panel **b**) plane as originated from progenitors with the indicated efficiency of microscopic diffusion (see text). Chemical composition as labeled.

multiplied by a factor two. One finds that for ages of the order of 10 Gyr the uncertainty in the efficiency of the microscopic diffusion moves, for each given cluster age, the TO magnitude over a range of about 0.16 mag., affecting the calibration of the TO luminosity in terms of age by $-0.7/+0.5$ Gyr. However, for larger ages the situation is getting worse, and at 15 Gyr the error becomes $-1.7/+1$ Gyr.

Let us now move to the ZAHB luminosity. Due to the (relatively) short HB evolutionary times the influence of diffusion on the structure of He burning stars is only the result of the influence on the H burning progenitors. As already predicted by Proffitt & VandenBerg (1991) and confirmed by evolutionary computations (Caloi et al. 1997, Castellani et al. 1997, Straniero et al. 1997) when diffusion is at work helium is ignited within a slightly larger He core (M_c^{He}) and with a lower He abundance in the envelope (Y_{HB}). Table 1 gives the values of these two structural parameters at the helium flash for a 0.8 $M_\odot$ stellar structure (Z=0.0002 Y=0.23) evolved under the various assumptions about the efficiency of diffusion.

The behavior of ZAHB luminosities can be easily predicted in terms of the well known relations connecting this luminosity with the mass of the He core and with the surface He abundance (see e.g. Sweigart & Gross 1976, Buzzoni et al. 1983, Bono et al. 1995). These predictions are indeed fully confirmed by detailed computations, whose results are given in Fig. 2 (panel a). Panel b) of the same figure shows the same ZAHBs in the observational plane (Mv, B-V). One finds that the uncertainty in the diffusion efficiency results in an uncertainty in the visual magnitude of RR Lyrae stars of about 0.06 mag.

Fig. 3 finally gives the predicted differences in magnitude between ZAHB (at the RR Lyrae gap) and TO as a function of age and for the various assumptions about the efficiency of diffusion. As expected, the decrease of the TO luminosity for a given age is partially balanced by the decrease of the ZAHB luminosity, so that the uncertainty in diffusion yields an uncertainty in ΔV(TO-HB) lower than 0.12 mag. As a result, one now finds that around t=10 Gyr the uncertainty in the calibra-

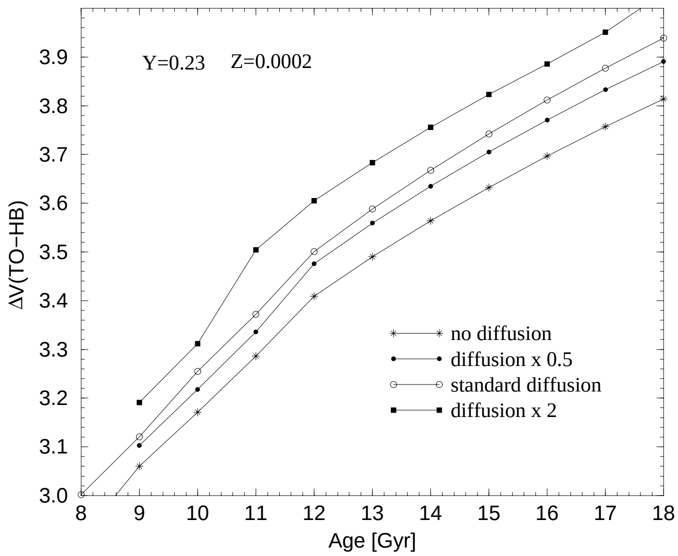

Fig. 3. The difference in magnitude between the ZAHB (at the RR Lyrae gap) and the TO as a function of the age for the labeled efficiency of microscopic diffusion (see text). Chemical composition as labeled.

tion of this parameter in terms of the cluster age (as far as the element diffusion is concerned) is $-0.5/+0.3$ Gyr, increasing up to $-1.2/+0.6$ Gyr at t=15 Gyr.

3. Discussion and conclusions

As a first point, let us notice that the influence of canonical element diffusion on both the TO and ZAHB magnitudes, as given in the previous section, appears in good general agreement with the discussion on that matter independently given by Straniero et al. (1997). According to all evolutionary evidence, one finds that the ΔV(HB-TO) method does depend on the efficiency of diffusion. However, when the dependence of HB luminosity on such an efficiency is taken into account, one finds that the uncertainty in the age calibration of this parameter is smaller than the uncertainty in the direct age-TO calibration one uses when deriving the cluster distance modulus by other distance calibrators. In this respect ΔV(TO-HB) could appear as a safer indicator of cluster ages.

However, one has also to remember that theoretical predictions on He burning stars are more uncertain than predictions on central H burning structures. In fact theoretical evaluations concerning He burning structures requires the intervention of additional physical mechanisms which do not affect MS and TO stars such as the neutrino production by weak interactions and electron conduction in electronic degenerate matter. A further source of uncertainty in the HB structures comes from the cross section of the 3α reaction, which governs the onset of the He flash and, thus, the He core mass of the ZAHB structure. To look a bit more into such a problem we performed some additional numerical experiments to investigate the sensitivity of HB luminosities to the above quoted physics inputs.

i) Plasma neutrinos: The estimated uncertainty in plasma neutrino energy losses is about 5% (Haft et al. 1994). Table 2 shows

Table 2. He core mass at the He flash (M_c^{He}) for a 0.8 $M_\odot$ with the labeled assumptions about the considered physical parameters (see text). The difference with respect to the model with standard diffusion (ΔM_c^{He}) is also reported. Chemical composition as labeled. H&L (69) indicates the adoption of Hubbard & Lampe (1969) coefficients for the conductive opacity.

	M_c^{He} [$M_\odot$]	ΔM_c^{He} [$M_\odot$]
	Z=0.0002 Y=0.23	
std. diffusion	0.5153	–
plasma ν +5%	0.5166	+0.0013
plasma ν −5%	0.5141	−0.0012
3α +15%	0.5143	−0.0010
3α −15%	0.5166	+0.0013
opacity +5%	0.5158	+0.0005
opacity −5%	0.5147	−0.0006
H&L (69) conduction	0.5148	−0.005

Table 3. The luminosity (LogL^{ZAHB}) and the visual magnitude (Mv^{ZAHB}) of ZAHB stars in the RR Lyrae region (at LogTe=3.85) under the labeled assumptions about the physical inputs (see text). The difference in the visual magnitude with respect to the model with standard diffusion (ΔM_V^{ZAHB}) is also shown. Chemical composition as labeled. H&L (69) indicates the adoption of Hubbard & Lampe (1969) coefficients for the conductive opacity.

	LogL^{ZAHB} [$L_\odot$]	M_V^{ZAHB}	ΔM_V^{ZAHB}
	Z=0.0002 Y=0.23		
no diffusion	1.748	0.386	−0.033
diffusion × 0.5	1.743	0.398	−0.021
std. diffusion	1.735	0.419	–
diffusion × 2	1.719	0.460	+0.041
plasma ν +5%	1.739	0.408	−0.011
plasma ν −5%	1.732	0.429	+0.010
3α +15%	1.732	0.426	+0.008
3α −15%	1.740	0.408	−0.011
opacity +5%	1.733	0.415	−0.004
opacity −5%	1.737	0.424	+0.005
H&L (69) conduction	1.718	0.461	+ 0.042

the corresponding variation of the He core at the Helium flash; the effects on the ZAHB luminosity (in the RR Lyrae region) are given in Table 3. Note the small asymmetry of the result, which is not a numerical noise but evidence of the much more marked asymmetry found by Raffelt & Weiss (1992) over a much large range of variation.

ii) Opacities: As discussed by Catelan et al. (1996) a completely satisfactory estimate of conductive opacities for RGB stars is still not available; in particular Catelan et al. (1996) pointed out that in RG evolutionary computations the widely adopted Itoh et al. (1983) formulation is used beyond its range of validity. In addition the estimate of the radiative opacity is affected by uncertainties, that cannot be precisely quantified, even if they are roughly evaluated around 5% for stellar interiors. By tentatively adopting a 5% uncertainty on the global (i.e. radiative and conductive) opacity one finds the variation of M_c^{He} reported in Table 2; the corresponding uncertainty on the ZAHB luminosity is again given in Table 3. However the adoption of the Hubbard & Lampe (1969) evaluation of the conductive opacity instead of the Itoh et al. (1983) formulation (as suggested by Catelan et al.) leads to a variation of the helium core $\Delta M_c^{He} \approx -0.005$ $M_\odot$ and the corresponding variation of the ZAHB luminosity is ΔLogL/$L_\odot$ $\approx$-0.017 (see Tables 2, 3).

iii) 3α reaction: The uncertainty on the 3α reaction rate is $\pm$15% (see e.g. Rolfs & Rodney 1988). Table 2 shows the values of He core at He ignition for a variation of the 3α efficiency within the experimental errors. Once again numerical experiments support the reality of the slightly asymmetrical results. Adopting from Sweigart & Gross (1976) $\Delta \mathrm{LogL}^{ZAHB}$ = 3.4 ΔM_c^{He}, one finds that for a decrease of the 3α rate by 15%, one expects a variation of the RR Lyrae luminosity of about ΔLogL/$L_\odot$ $\approx$ 0.006; numerical experiments again perfectly confirm this prediction.

Table 3 summarizes the variations of the RR Lyrae luminosity due to the uncertainties of the considered physical parameters; one clearly sees that the indetermination in the efficiency of element diffusion and in the conductive opacity is the main source of uncertainty. If one decides to be very conservative, one can simply add the errors given in the table to derive that theory gives for the RR Lyrae ZAHB luminosity an uncertainty of δMv^{ZAHB} =+0.106/-0.047 mag.

As for the calibration of ΔV(TO-HB) in terms of cluster age, data in Table 3 show that in addition to the uncertainties in the efficiency of diffusion one is facing further uncertainties on Mv^{ZAHB} and thus on ΔV(TO-HB) as given by $\delta Mv^{ZAHB} = -0.026/+0.065$. Looking again at Fig. 3, this implies an additional error in the calibration by $-0.5/+0.3$ Gyr. By adding this values to the uncertainties from element diffusion one finds for the calibration of ΔV(TO-HB) in terms of age a theoretical uncertainty of $-1.0/+0.6$ at 10 Gyr, growing to $-1.7/+0.9$ at 15 Gyr. On this basis, one finds that theoretical uncertainties on ages from ΔV(TO-HB) appear of the same order of magnitude of the uncertaintes on ages from Mv^{TO}, as derived when the cluster distance modulus is known without error.

Acknowledgements. It is a pleasure to thank A. Weiss for the kind hospitality at Max Plank Institut for Astrophysics in Garching and for useful discussions.

References

Bono G., Castellani V., Degl'Innocenti S., Pulone L., 1995, A&A 297,115
Buzzoni A., Fusi Pecci F.,Buonanno R., Corsi C.E., 1983, A&A 128, 94
Caloi V., D'Antona F., Mazzitelli I., 1997, A&A 320, 823
Cassisi S., Castellani V., Degl'Innocenti S., Weiss A., 1998a, A&AS 129, 267
Cassisi S., Castellani V., Degl'Innocenti S., Salaris M., Weiss A., 1998b, A&AS 133, 1
Castellani V., Ciacio F., Degl'Innocenti S., Fiorentini G., 1997, A&A 322, 891
Castelli F., Gratton R.G., Kurucz R.L., 1997a, A&A 318, 841
Castelli F., Gratton R.G., Kurucz R.L., 1997b, A&A 324, 432
Catelan M., de Freitas Pacheco J.A., Horvath J.E., 1996, ApJ 461, 231
Chaboyer B. 1995, ApJ 444, L9
Fiorentini G., Lissia M., Ricci B. 1998, A&A, submitted
Haft M., Raffelt G., Weiss A., 1994, ApJ 425, 222
Hubbard W.B., Lampe M., 1969, ApJS 163, 297
Itoh N., Mitake S., Iyetomi H., Ichimaru S., 1983, ApJ 273, 774
Pont F., Mayor M., Turan C., VandenBerg D.A., 1998, A&A 329, 87
Proffitt C.R., VandenBerg D.A., 1991, ApJS 77, 473
Raffelt G., Weiss A., 1992, A&A 264, 536
Rolfs C.E., Rodney W.S., 1988, Cauldrons in the Cosmos. The University of Chicago Press, Chicago and London
Straniero O., Chieffi S., Limongi M., 1997, ApJ 490, 425
Sweigart A.V., Gross P.G. 1976, ApJS 32, 367