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Intermediate-age metal deficient stellar populations: the case of metallicity Z=0.00001

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Abstract. We investigate the evolution of metal deficient stars, presenting H-burning isochrones covering cluster ages from 800 Myr to 7 Gyr. Evolutionary evidences for selection effects in the metallicity distribution of very metal poor H-burning red giants are reported. The evolution of stars during central and shell He burning is further investigated, discussing the occurrence of He burning pulsators as a function of cluster age.

Key words: stars: evolution – stars: HR diagram – stars: horizontal branch – stars: Population II – galaxies: stellar content

1. Introduction

Since the pioneering work by Bond (1970), in the past few decades much observational effort has been devoted to searching for very metal poor stars. As a consequence, there is increasing evidence for a population of metal deficient stars in the Galactic Halo (see, e.g., Molaro & Castelli 1990, Primas et al. 1994, Sneden et al. 1994) and, in turn, there is a renewed interest in theoretical constraints on the evolution of very metal poor objects. As matter of fact, even if the approach to the evolution of metal deficient stars dates to the early seventies, this argument is still open to investigation. In a preliminary paper Cassisi & Castellani (1993) presented a rather extensive investigation of the theoretical scenario concerning these peculiar stellar objects. However, their analysis was mainly devoted to the study of the 'Red Giant Phase Transition' (see below) in low mass stars as well as to the determination of the lower mass limit (M^{up}) for quiet carbon ignition in more massive stars. This scenario has been recently improved by Cassisi et al. (1996; Paper I) who investigated H and He burning phases for low mass, metal deficient stars, presenting theoretical isochrones for ages in the range 7 - 15 billion of years and discussing the evolutionary expectations for RR-Lyrae stars.

According to these results, one finds that old Population III and Population II stars have been rather extensively investigated in the literature. However, the evidence is increasing for dwarf spheroidals being metal poor systems, but not as old as galactic globular clusters are. Such an evidence has recently suggested the opportunity to extend to larger masses evolutionary computations concerning metal poor stars. Accordingly, Castellani & Degl'Innocenti (1995) have discussed the evolutionary behavior of stars up to about $2M_{\odot}$, for the two selected choices on the amount of heavy elements: $Z = 10^{-4} - 4 \cdot 10^{-4}$, extending in such a way previous investigations of metal poor stars to cluster ages lower than 1 Gyr. However, suggestions have been advanced for the occurrence in dwarf spheroidals of a not negligible spread of metallicities, with the possible occurrence of stars with even lower values of Z. On this basis, Caputo & Degl'Innocenti (1995) have recently speculated about the possible occurrence of metal deficient He burning pulsators. Due to the lack of investigation on the evolutionary scenario concerning similar metal deficient, intermediate age stellar systems, it is obviously interesting to extend to lower metallicities the evolutionary scenario presented in the above referred literature.

This paper will present the results of such an investigations, as performed exploring the evolutionary behavior of stars with $Z = 10^{-5}$, a metallicity value adopted as a suitable lower limit for the amount of heavy elements in dwarf spheroidal systems. In Sect. 2 we will discuss the H burning evolution for the given choice on the stellar metallicity. Starting from these results, Sect. 3 will deal with the results concerning He burning phases. A final discussion will close the paper.

2. The H burning phase in metal deficient stars

In order to extend the theoretical scenario concerning stars with $Z = 10^{-5}$ down to cluster ages of about 1 Gyr, evolutionary tracks already presented in Paper I for the quoted metallicity have been implemented with new tracks for suitable choices on the stellar masses. All the computations have been performed adopting a cosmological abundance of He as given by $Y = 0.23$.

As well known, the modality of He ignition significantly depends on the original mass of the evolving giant. For each

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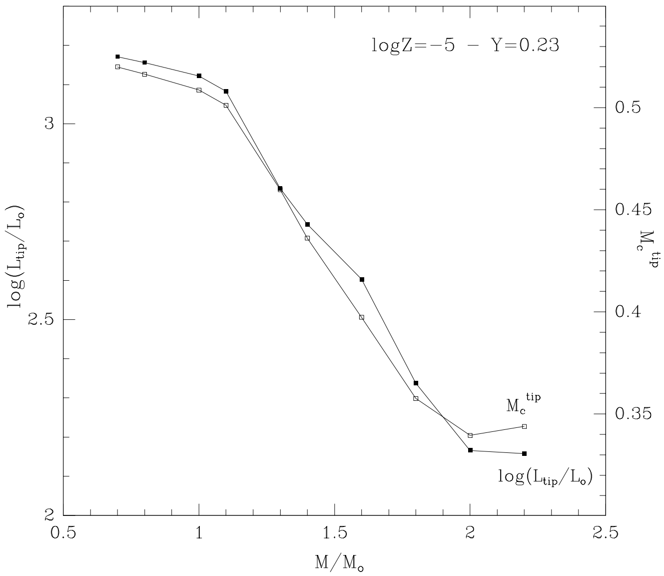

Fig. 1. The luminosity of the RGB tip and the mass of the helium core at the helium ignition versus the total star mass when Z=10^{-5}.

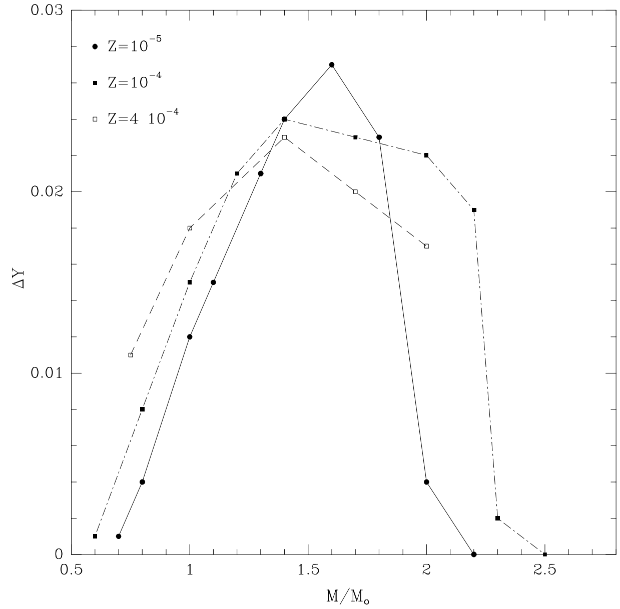

Fig. 2. The amount of extra-helium brought to the surface by the first dredge up for all the computed models. For the sake of comparison, the results concerning two different assumptions about the stellar metallicity are reported.

Table 1. Selected evolutionary parameters at the He ignition: 1) the star mass, 2) the stellar luminosity at the tip of the RGB, 3) the mass (in solar unit) of the He core, 4) the amount of extra-helium brought at the surface by the first dredge up and 5) the age (in Gyrs) of the star.

$M/M_\odot$	$\log(L/L_\odot)_{tip}$	M_c^{tip}	ΔY	t_{HeF}
1.1	3.083	0.501	0.015	5.04
1.3	2.835	0.460	0.021	2.89
1.4	2.743	0.436	0.024	2.27
1.6	2.603	0.397	0.027	1.47
1.8	2.338	0.358	0.023	1.01
2.0	2.166	0.339	0.004	0.72
2.2	2.158	0.344	0.000	0.53

given stellar population (i.e., for each assumed value of Y and Z), one may define a critical mass M_{HeF} as the upper mass limit for stars experiencing strong electron degeneracy of the He core during the H shell burning phase and - thus - igniting He through one or more violent He flashes. One finds that evolutionary features of red giant (RG) stars with masses around M_{HeF} change in a remarkable way in a range of only few tenths of solar mass, an occurrence already known as '*Red Giant Branch Transition*' (RGT) (see Sweigart, Greggio & Renzini 1989, hereafter SGR, Sweigart, Greggio & Renzini 1990, Castellani et al. 1992).

The behavior of Z=10^{-5} models through the transition is shown in Fig. 1, which shows the dependence of M_c^{tip} (the mass of the He core at the He ignition) and L_{tip} (the star luminosity at the tip of RGB) on the stellar mass. According to Sweigart & Gross (1978) and SGR, the onset of the helium flash has been taken at the model where the contribution of 3α reactions to the energetic reaches $100L_\odot$; for structures which quietly ignite helium, the He ignition has been alternatively fixed at the first appearance of a convective core. The sudden variation of L_{tip} around M=$1.5M_\odot$ indicates that this mass is near the transition between low mass stars developing full degenerate Helium cores and more massive stars where electron degeneracy is progressively removed. As in previous investigations, if one defines the critical mass M_{HeF} as the mass of the star having at the He ignition a He core mass equal to the average value between the He core of fully degenerated structures and the absolute minimum in M_c^{tip}, when Z=10^{-5} one finds M_{HeF} of the order of $1.45M_\odot$. Accordingly, let us define a transition age, as the age of a cluster where stars with masses M=M_{HeF} are just at their He ignition. Table 1 reports selected evolutionary parameters for all the computed models, allowing a quantitative inspection of the RGB transition.

Fig. 2 compares the amount of extrahelium brought to the surface by the first dredge up with similar data but for the larger metallicities investigated in Castellani & Degl'Innocenti (1995). As already discussed in Castellani & Degl'Innocenti (1995), for each given metallicity one finds a stellar mass separating the regime of low mass stars, where ΔY increases when the stellar mass is increased, from more massive stars with opposite behavior. Such an occurrence as well as the dependence of ΔY on the star metallicity can be easily understood in terms of the discussion given by Castellani & Degl'Innocenti (1995).

Fig. 3a shows the dependence of the critical mass M_{HeF} on star metallicity. In this figure, present results have been implemented with similar data given by Cassisi & Castellani (1993) or by SGR for lower or larger metallicities, respectively. The dependence of M_{HeF} on Z has been already discussed (see Cassisi and Castellani 1993) and this discussion will not be repeated here. As a relevant point, Fig. 3b discloses the dependence of

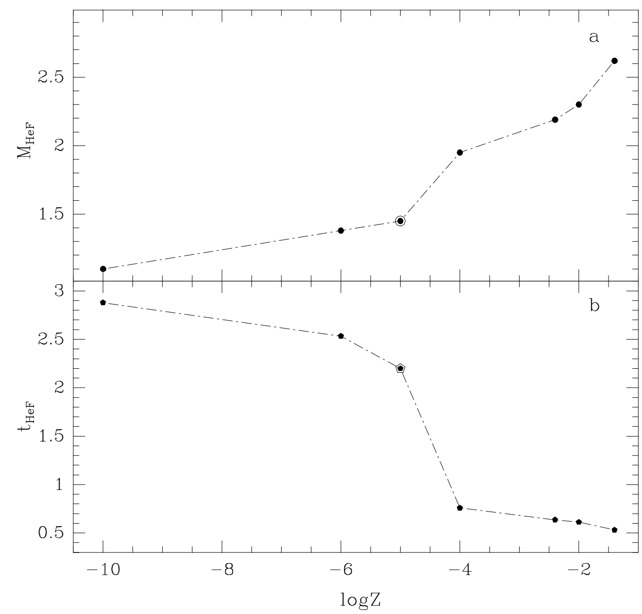

Fig. 3a and b. The critical mass M_{HeF} (in solar mass) (**a**) and the age (in Gyrs) of a cluster with M_{HeF} at the He ignition (**b**) versus the global amount of heavy elements.

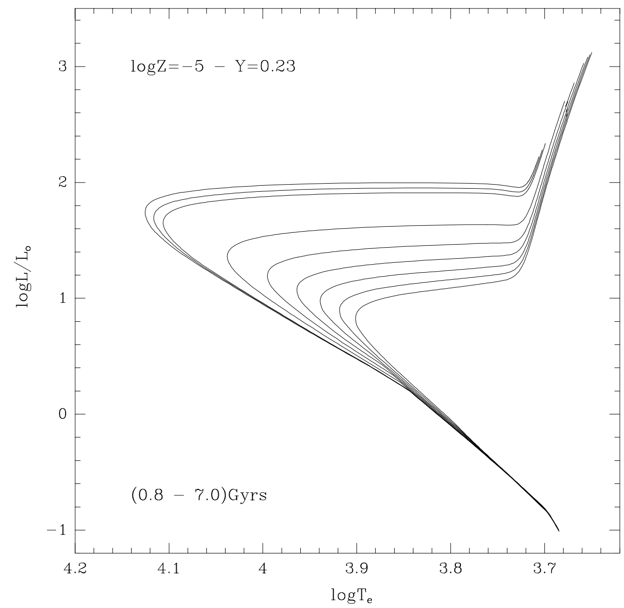

Fig. 4. Cluster isochrones for H burning phases and for the labeled range of ages. The interval is 100 Myr for ages lower than 1 Gyr and 1 Gyr for larger ages.

the transition age on the cluster metallicity. It appears that when Z=10^{-5} the transition requires ages of the order of about 2.2 Gyr, i.e., a much larger age than for the Z=10^{-4} case. As a consequence, in a dwarf galaxy with star metallicities ranging from Z=10^{-5} to Z=10^{-4} and ages around 1 Gyr, the red giant branch is expected to be populated by the more metal rich stars only. As a result, one finds that the distribution of metallicity of RG cannot taken in all cases as a bona fide indicator of the distribution of star metallicity in intermediate-age metal poor systems.

Evolutionary models, as computed for the case Z=10^{-5} allow us to extend toward lower ages the set of isochrones presented in Paper I. This is shown in Fig. 4 where we report selected isochrones for H burning models covering cluster ages from 0.8 to 7Gyrs.

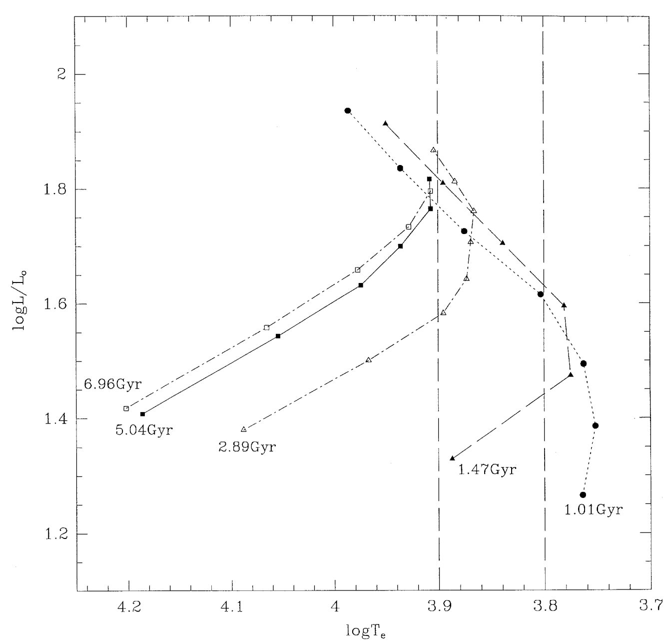

Fig. 5. The locus in the HR diagram of ZAHB structures for the various labeled assumptions about the cluster age. The mass of the various models is reported in Table 2.

3. The evolution along the He burning phase

Evolutionary data for H burning stars, as given in the previous section, allow to investigate the evolution of stars during the He burning phase, following a procedure quite similar to that used in investigating the evolutionary properties of low mass He burning stars in galactic globular clusters. For each assumption concerning the chemical composition and the age of a cluster, one obtains from H-burning evolutionary computations the mass of stars at the He ignition (M_{RG}), the He core mass (M_c^{tip}) and the amount of extrahelium ΔY brought at the surface of these stars by the first dredge up. When all these quantities are known, Zero Age Horizontal Branch (ZAHB) models can be obtained, computing the sequence of stellar structures burning at the center of a He core of mass M_c^{tip}, surrounded by an envelope enriched by ΔY, with a global mass fulfilling the condition that $M_{tot} = M_c^{tip} + M_{envelope} \leq M_{RG}$.

However, at variance with the case of old globular cluster stars, the value of M_c^{tip} is now sensitively depending on the value of M_{RG}, i.e. on the cluster age. Since the luminosity of the ZAHB is largely dependent on the mass of the He core, one expects a large dependence of the ZAHB luminosity on the age of the

Table 2. Selected evolutionary parameters for He burning stellar models. The stellar mass, the luminosity and the effective temperature of the ZAHB model and the central He burning lifetime (in $10^6 yrs$) are reported in the order for the various labeled assumptions about the cluster age, i.e., for the given mass of the original progenitor.

$M/M_\odot$	$\log(L/L_\odot)_{ZAHB}$	$\log T_{e\,ZAHB}$	$\tau_{He-burn}$
$t_{HeF} = 5.04Gyr - M_{pr} = 1.1M_\odot$			
0.60	1.408	4.186	112
0.70	1.543	4.054	103
0.80	1.631	3.974	97
0.90	1.699	3.936	93
1.00	1.764	3.907	90
1.10	1.816	3.908	88
$t_{HeF} = 2.89Gyr - M_{pr} = 1.3M_\odot$			
0.60	1.380	4.088	142
0.70	1.500	3.967	130
0.80	1.582	3.895	124
0.90	1.642	3.873	119
1.00	1.706	3.869	114
1.10	1.760	3.866	110
1.20	1.812	3.884	107
1.30	1.866	3.904	104
$t_{HeF} = 1.47Gyr - M_{pr} = 1.6M_\odot$			
0.60	1.329	3.887	221
0.80	1.474	3.775	193
1.00	1.595	3.781	173
1.20	1.704	3.839	158
1.40	1.809	3.895	145
1.60	1.912	3.950	132
$t_{HeF} = 1.01Gyr - M_{pr} = 1.8M_\odot$			
0.60	1.266	3.764	302
0.80	1.386	3.752	263
1.00	1.494	3.763	233
1.20	1.615	3.803	209
1.40	1.725	3.875	188
1.60	1.835	3.936	170
1.80	1.935	3.986	153

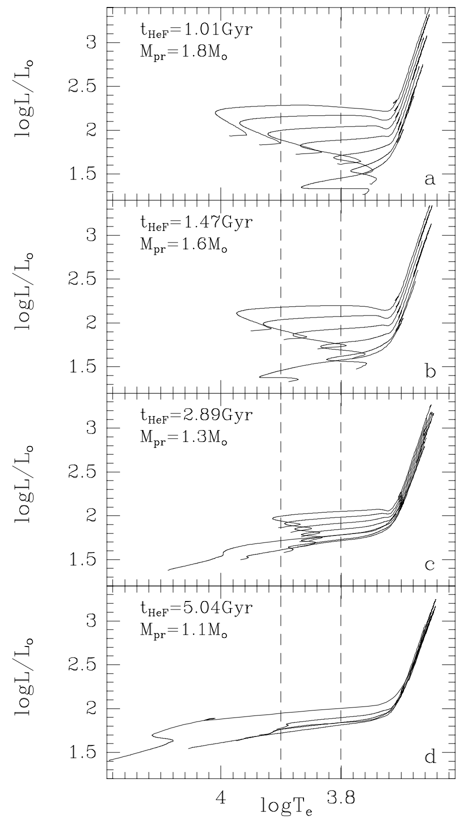

Fig. 6a–d. The evolutionary path in the HR diagram of He burning models for the labeled assumptions about the cluster age. The initial mass of the progenitor (M_{pr}) is also reported. The vertical dashed lines sketch the temptative location of the strip for pulsational instability.

stellar system. This occurrence is shown in Fig. 5, where ZAHB locations for the various labeled assumptions about the cluster ages are plotted. Table 2 gives selected evolutionary quantities for all the computed ZAHB models.

As early recognized by Caloi, Castellani & Tornambé (1978), inspection of Fig. 5 reveals that increasing the total mass the effective temperature of a ZAHB model decreases until a minimum temperature is reached and the temperature starts increasing with mass. As for the origin of this minimum, one finds that for each given value of M_c^{tip}, increasing the mass of the envelope, the temperature in the H burning shell continuously increases whereas the density decreases. Central conditions show an opposite behavior, since increasing the stellar mass the central density increases and the temperature, slightly, decreases. As a result, the ratio between the luminosity due to H or He burning monotonously increases when the mass of the envelope is increased over the whole explored range of masses. Thus the occurrence of the minimum in temperature cannot be related to the relative efficiency of the burning. The occurrence of this minimum can be much more simply related to the evidence that increasing the stellar mass (i.e. the mass of the envelope), the core and shell-burning regions behave more and more as a central energy source. As a consequence, the more massive ZAHB models shift towards larger effective temperature approaching a MS-like location.

Figs. 6a-d show the evolutionary paths in the HR diagram of the models in Fig. 5 during the phase of central and shell He burning. As already recognized for larger metallicity by Caputo & Degl'Innocenti (1995), one finds that the range in magnitude covered by the red ZAHB branch increases when the cluster age decreases. Thus the observed range of magnitudes can be used to put an upper limit to the age of stellar systems even in the $Z = 10^{-5}$ case. As for the post-HB evolution, all computed models have envelopes massive enough to approach their Hayashi tracks during the double shell burning phase.

In order to investigate the occurrence of variable stars, both Figs. 5 and 6a-d report the temptative location of the region for

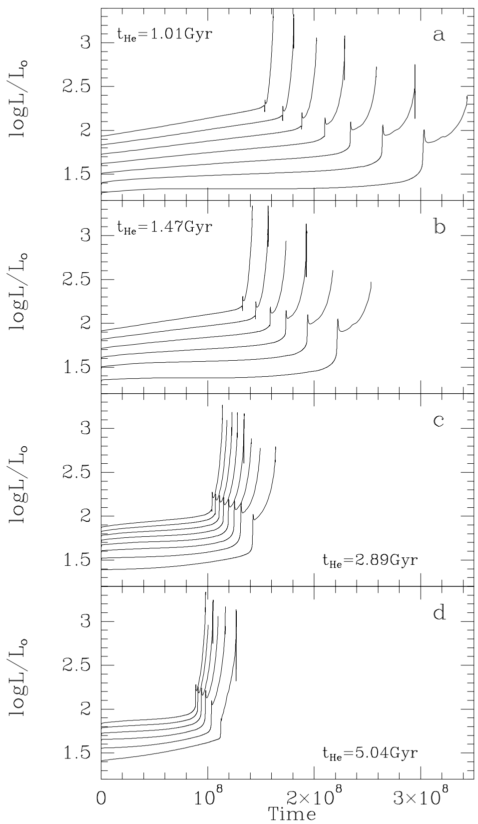

Fig. 7a–d. The behavior with the time of the luminosity during the central and shell He burning phases for the labeled assumptions concerning the cluster ages.

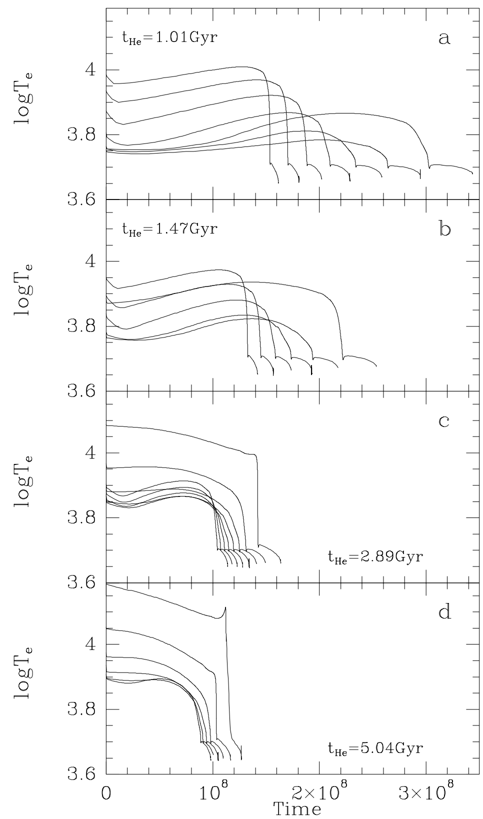

Fig. 8a–d. The behavior with the time of the effective temperature for all models computed in the present work during the central and shell He burning phases for the labeled assumptions concerning the cluster ages.

pulsational instability. As well known, old very metal poor systems cannot produce ZAHB pulsators since the ZAHB locations are in all cases hotter than the instability strip. According to Cassisi et al. (1996), this is the case for metallicities log$Z \leq -5$ and ages larger than about 7 Gyrs. As expected, now one finds that for ages smaller than - about - 5.1 Gyrs metal deficient clusters start allowing ZAHB pulsators. Decreasing the cluster age, the range of masses in the instability strip increases. For ages of about 2.8-2.9 Gyrs one finds that all ZAHB models more massive than $0.8 M_\odot$ fall within the instability strip. In similar clusters one should expect an anomalous clump of He burning pulsating stars. However, a detailed discussion on the pulsational scenario concerning similar metal poor variables is beyond the aim of the present work. For a deeper investigation on the pulsational properties of these metal poor stars, we will address to a forthcoming paper (Bono et al. 1996).

Figs. 7a-d and 8a-d show the time evolution of luminosity and effective temperature of the models in Figs. 6 during both central and shell He burning phases.

Without entering into a detailed discussion, let us only notice the progressive increase of the He central burning lifetimes when the cluster age is decreased. This is the expected result of the corresponding decrease of the mass of the He-core in ZAHB models. As a consequence, one expects an increasing evidence for He-burning giants which will eventually dominate the cluster giant population.

4. Conclusions

This paper investigated the evolutionary properties of relatively massive, metal deficient stars. The first part of the investigation has been devoted to H burning stars, presenting selected isochrones for ages in the range 800 Myr - 7 Gyr, increasing the range of ages covered by previous investigations.

Selected sets of HB models have been computed under different assumptions about the ages of a stellar system. We confirm the results already given for larger stellar metallicities about the possible, and sometime probable, occurrence of anomalous, overluminous radial pulsators, in relatively young, metal deficient system.

Both evolutionary tracks and isochrones are available by electronic mail upon request to cassisi@astrte.te.astro.it.

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References

Bond H.E. 1970, ApJS 22, 117
Bono G., Caputo F., Cassisi S., Piersimoni A.M. & Santolamazza P. 1996, *in preparation*
Caloi V., Castellani V. & Tornambé A. 1978, A&AS 33, 169
Caputo F. & Degl'Innocenti S. 1995, A&A 298, 833
Cassisi S. & Castellani V. 1993, ApJS 88, 509
Cassisi S., Castellani V. & Tornambé A. 1996, ApJ 459, 298
Castellani V., Chieffi A. & Straniero O. 1992, ApJS 78, 517
Castellani V. & Degl'Innocenti S. 1995, A&A 298, 827
Molaro P. & Castelli F. 1990, A&A 228, 426
Nemec J.M., Nemec A.F.L. & Lutz T.E. 1994, AJ 108, 222
Primas F., Molaro P., Castelli F. 1994, A&A 290, 885
Sneden C., Preston G.W., McWilliam A., Searle L. 1994, ApJ 431, L27
Sweigart A., Greggio L., & Renzini A. 1989, ApJS 69, 911 (SGR)
Sweigart A., Greggio L., & Renzini A. 1990, ApJ 364, 527
Sweigart A. & Gross P. 1978, ApJS 36, 405

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