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Theoretical zero age main sequences revisited

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Abstract. Zero Age Main Sequence (ZAMS) models with updated physical inputs are presented for selected assumptions about the chemical composition, covering the ranges 0.6 $<$ M $<$ 1.2 $M_{\odot}$, 0.0001 $<$ Z $<$ 0.04, 0.23 $<$ Y $<$ 0.34. The HR diagram location of the ZAMS as a function of Y and Z is discussed both in the theoretical (logL, $\log T_{eff}$) and in the observational (M_v, B-V) diagrams, showing that the V magnitude presents an increased dependence on Z to be taken into account when discussing observational evidences. Analytical relations quantifying both these dependences are derived. Implications for the galactic helium to heavier elements enrichment ΔY/ΔZ are finally discussed.

Key words: stars: general – stars: Hertzsprung–Russel (HR) and C-M diagrams

1. Introduction

Long time ago, the observational evidence for MS stars has been the very first challenge for the theory of stellar structure and the prediction for underluminous metal poor MS stars has been among the very first success of the theory. Since that time, the location in the Color Magnitude (CM) diagram of the Zero Age Main Sequence (ZAMS) and its dependence on the adopted chemical composition keeps being a relevant ingredient for the investigation of stellar clusters and in particular for distance determinations through MS fitting. The issue is now matter of a renewed interest vis-a-vis the absolute magnitudes made available by the Hipparcos satellite for a large amount of stars.

In this context, theoretical predictions concerning the ZAMS are also connected with the still open problem of the ratio ΔY/ΔZ marking the enrichment of interstellar medium during the nuclear evolution of galactic matter. From an observational point of view, for any given range of metallicities the location of the related main sequences depends on the corresponding variation in Y, which thus governs the observed ZAMS broadening. In spite of the difficulty of the procedure, which is affected by uncertainties on cluster reddening, metallicity and distance modulus, several evaluations of the quoted ratio have been provided in last decades, by using suitable relations between the main sequence thickness and chemical composition variations (Faulkner 1967, Perrin et al. 1977, Pagel 1995, Cayrel de Strobel & Crifo 1995, Fernandes et al. 1996). However, one has to notice that the related theoretical scenario appears far from being firmly established, and the diffuse belief that the effects of Y and Z on the ZAMS location cancel out for $\Delta Y/\Delta Z \approx 5 \div 5.5$ (see e.g. Fernandes et al. 1996, Mermilliod et al. 1997) runs against the theoretical evidence recently given by Pagel & Portinari (1998) for which ΔY/ΔZ =6 should produce still a not negligible broadening.

Owing to the relevance of this issue, in this paper we will revisit theoretical predictions about the location of ZAMS models both in the theoretical (logL, $\log T_{eff}$) and observational (M_v, B-V) diagrams. Taking into account the increasing amount of observational data, the investigation will be extended over a rather large range of both Z and Y values, covering the ranges Z=0.0001–0.04 and Y=0.23–0.34. In Sect. 2 we present our models for selected chemical compositions, whereas in Sect. 3 we derive suitable analytical relations, discussing the implications for the ΔY/ΔZ ratio.

2. ZAMS and/or MS models

As usual, in the following we will use the term “Zero Age Main Sequence” (ZAMS) to indicate the HR diagram locus of stellar models which are just starting central H burning with the timescale of H consumption in the stellar interior. More in detail, the term refers to the first H burning model which has settled in its Main Sequence phase after having reached the equilibrium of the secondary elements participating in the various H burning reactions. Accordingly, all these “Zero Age” models have already experienced a phase of nuclear burning, with time scales which largely depend on the stellar mass tough, in all cases, much shorter than the expected central H burning MS phase. In this context, one expects that ZAMS stars will evolve increasing their luminosity, till reaching the exhaustion of central H. However, as discussed by Fernandes et al. (1996), for any reasonable assumption about the stellar ages, one can safely assume that all the stars fainter than $M_v \sim 5.5$ are practically unaffected by evolution, so that below this luminosity stars are expected to be

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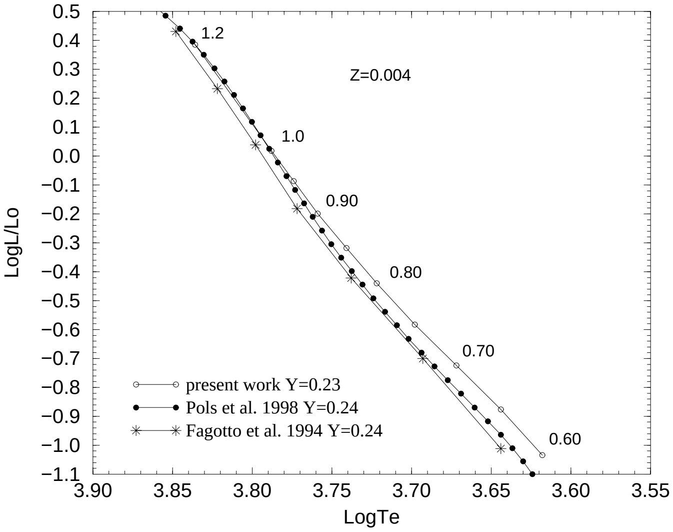

Fig. 1. Comparison among the HR diagram position of ZAMS models with Z=0.004 by Pols et al. 1998, Fagotto et al. 1994 and by the present work. Helium abundance as labeled.

in any case close to their ZAMS location (see also Lebreton et al. 1997 and Pagel & Portinari 1998).

Bearing in mind such a scenario, we used the FRANEC evolutionary code (Straniero & Chieffi 1991) to compute ZAMS models for selected choices about the original chemical composition for stellar models covering the mass range 0.6–1.2 $M_\odot$. The input physics, but the equation of state (EOS), is as in Cassisi et al. (1998), who included all the most recent evaluations of the various physical ingredients given in the literature. The interested reader can find in the above quoted paper a complete description of the adopted physics together with a detailed discussion of the influence of the "new" inputs on stellar models. Regarding the EOS, one finds that the tabulation by Rogers et al. (1996) used in Cassisi et al. (1998) does not allow a full coverage of the range of pressures and temperatures required by our grid of models.

To overcome this problem, we adopted the extended EOS tabulation given by Straniero (1988) on the basis of the free-energy minimization method, which takes also into account electron degeneracy and Coulomb corrections. In the low temperature region we implemented this EOS with the Saha equation, which includes the pressure ionization contribution, according to the method described by Ratcliff (1987). Comparison with MS models computed with OPAL EOS (Rogers et al. 1996), as allowed for selected structures, shows that Straniero's EOS gives slightly cooler models (by about 100 K) with quite a similar dependence on the adopted chemical composition. Comparison with similar models presented in the literature, as given in Fig. 1, shows that at the larger luminosities our results appear in excellent agreement with the recent computations by Pols et al. (1998), becoming redder at the lower luminosities. This is probably due to the different EOS, since the above quoted authors adopt an improved version of the Eggleton et al. (EFF, 1973) equation of state (see Pols et al. (1995) and Christensen-Dalsgaard & Dappen (1992) for a discussion on EFF EOS).

The difference with models by Fagotto et al. (1994) has probably a similar origin, though we have not found in the literature a detailed description of the EOS used by these authors. Since, in principle, our adopted EOS should be at least as accurate as the EOS adopted in previous investigations on the matter, data in Fig. 1 can be taken as an evidence that a precise location of the ZAMS deserves still more work. However, comparison among the quoted results discloses a rather good agreement as far as the effects of chemical composition are concerned, so that one can be confident that current models can give a realistic information about the dependence on the chemical composition.

Fig. 2 shows the location, in both the theoretical (left panel) and the observational (right panel) HR diagram, of the present ZAMS, as computed for stellar masses ranging from 0.6 to 1.2 $M_\odot$ and for the labeled values of chemical composition. Magnitude and colors have been produced adopting Kurucz's (1992) model atmospheres which, to our knowledge, provide the only available set of models covering the whole range of metallicities (up to Z = 0.04) explored in this paper.

As well known, at any fixed effective temperature, both the theoretical and the observational ZAMS get fainter as the metallicity decreases or the helium content increases. However, Fig. 2 shows that such a behavior appears sensitively enhanced in the observational plane, due to the dependence of both the color and the bolometric correction on the star metallicity. Thus the observed MS broadening cannot properly be discussed on the basis of the behavior of M_{bol} only, as sometime given in the literature.

Again in Fig. 2 one finds that ZAMS run nearly parallel each other over a rather large portion of the diagrams, allowing the derivation of analytical relations for the dependence on Y and Z we will discuss in the next section.

In this context, one has to notice that the HR diagram location of the models is dependent on the assumption about the efficiency of superadiabatic convection which affects the external layers of most of the models in Fig. 2. To minimize this problem we will restrict our investigation (see Sect. 3) to the lower portion of the main sequence, where superadiabaticity effects are expected to be negligible (see, e.g., VandenBerg et al. 1983, Pagel & Portinari 1998).

3. The dependence of ZAMS position on Y and Z

Interpolation among the bolometric magnitudes at $\log T_{eff}$=3.70 gives:

$$\mathrm{M}_{\mathrm{bol}(\log\mathrm{T}_{\mathrm{eff}}=3.70)} = 3.219 + 2.425\,\mathrm{Y} - 1.411\,\log\mathrm{Z} - 0.176(\log\mathrm{Z})^2 \quad (1)$$

which is valid over the whole range of explored compositions with a R.M.S = 0.010 and which can be used to constrain the shift of the ZAMS when varying Y and/or Z.

Note that the fit of all the data requires a quadratic dependence on logZ. When considering the dependence of the visual magnitude on Y and Z at fixed B-V one cannot find a reference color for a suitable coverage of the ZAMS all over the explored range of metallicities (see Fig. 2). Thus we choose

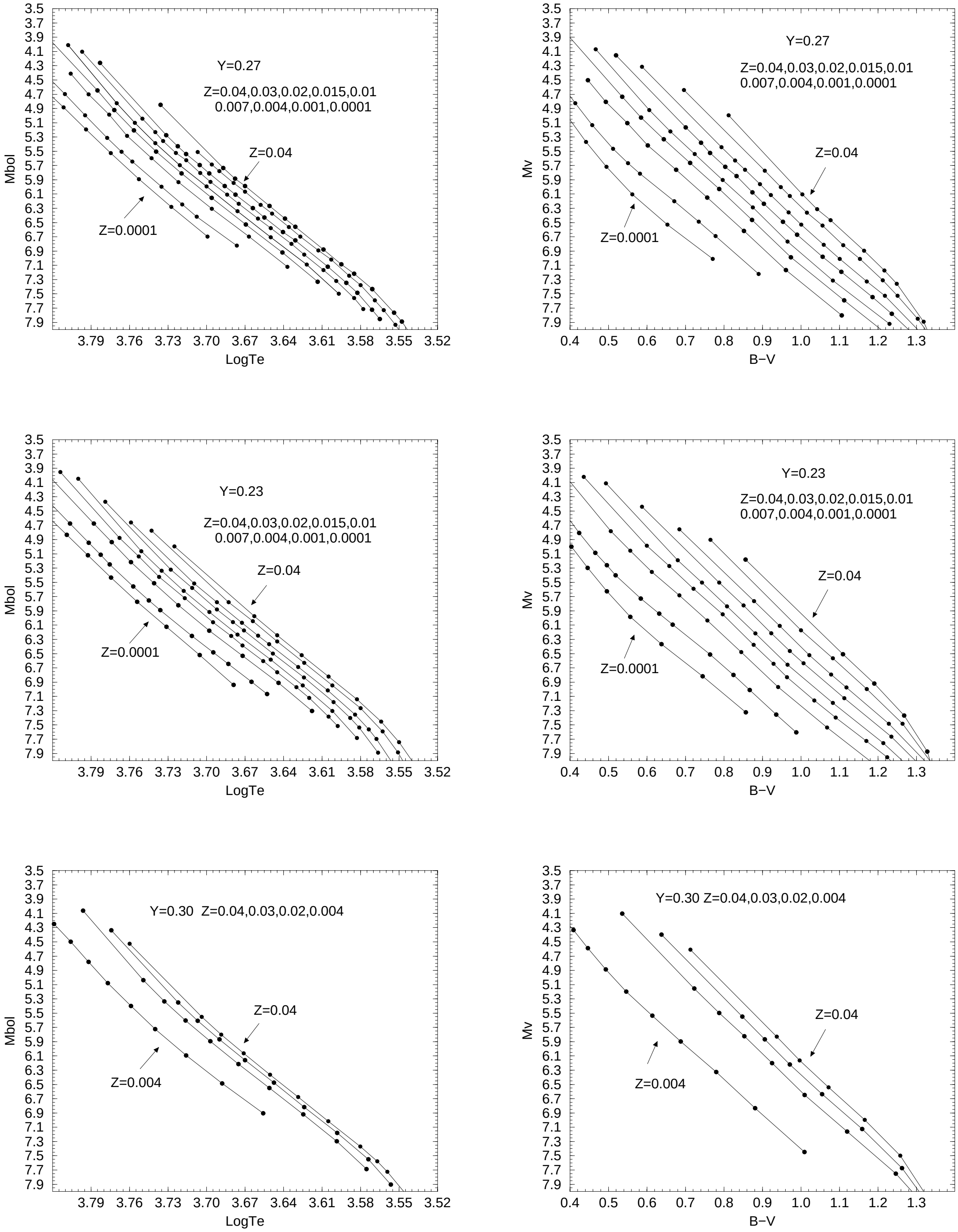

Fig. 2. ZAMS models in the theoretical (left panels) and observational (right panels) HR diagram for the labeled assumptions about the star chemical compositions and for stellar masses ranging from 0.6 to 1.2 $M_\odot$. Data in the left panel assume for the Sun M_{bol}= 4.72.

two B-V values according to selected ranges of metallicities, namely: B-V=0.8 for Z $\leq$ 0.01 and B-V=1.1 for Z $\geq$ 0.01. The two corresponding relations are:

$$\mathrm{M}_{\mathrm{v}(Z\leq 0.01, B-V=0.8)} = -0.184 + 16.064Y + (-6.258 + 15.686\ \mathrm{Y}) \cdot \log \mathrm{Z} + (-1.433 + 4.551\ \mathrm{Y}) \cdot (\log \mathrm{Z})^2 \qquad (2)$$

with a R.M.S.=0.013.

$$\mathrm{M}_{\mathrm{v}(Z\geq 0.01, B-V=1.1)} = 2.105 + 1.404\ \mathrm{Y} + (-1.861 - 1.542\ \mathrm{Y}) \cdot \log \mathrm{Z} + (-0.179\text{–}0.373\mathrm{Y}) \cdot (\log \mathrm{Z})^2 \qquad (3)$$

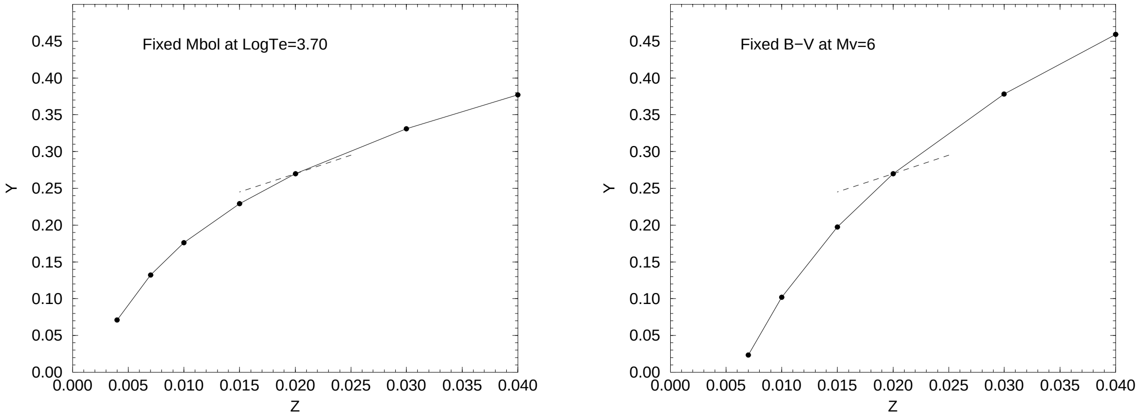

Fig. 3. Left panel: the relation between Y and Z in the assumption of δM$_{bol}$=0 with respect to the solar (Z=0.02 Y=0.27) value at fixed temperature (logT$_{eff}$=3.70) (see text). The dashed line indicates ΔY/ΔZ= 5 relation. Right panel: as in the left panel but for δ(B-V)=0 at M$_v$=6 mag.

with a R.M.S. = 0.005.

However, at M$_v$=6 mag, one can find an analytical relation connecting the B-V values to Y and Z, all over the explored range of chemical compositions, as given by:

$$(\mathrm{B-V})_{(\mathrm{M_v=6})} = 1.663\text{–}0.473\,\mathrm{Y} + 0.467\,\mathrm{logZ} + 0.055(\mathrm{logZ})^2 \tag{4}$$

with a R.M.S.= 0.004.

Now we are in the position of discussing the predicted effects of the various correlations between Z and Y. Let us first take as "reference value" the bolometric magnitude for the solar ZAMS (Z=0.02, Y=0.27) at fixed temperature (logT$_{eff}$=3.70) to investigate which variation of Y could be able to balance a variation in metallicity. Note that this is just a theoretical experiment, since we know that metallicity does cause a spread in the ZAMS location (see e.g. again Pagel & Portinari 1998).

Fig. 3 (left panel) shows, for each given assumption on Z, the values of Y for which one has the same bolometric magnitude (at logT$_{eff}$=3.70) as the Z=0.02 Y=0.27 ZAMS, that is the value of Y for which one would expect no spread of the MS due to chemical composition. The dashed line indicates the ΔY/ΔZ = 5 relation. One may notice that in this case present theoretical predictions are in reasonable agreement with the slope ΔY/ΔZ$\approx$5, as often referred in the literature, but only in a restricted metallicity range around Z=0.02. However, the right panel of Fig. 3 shows the relation between Y and Z needed to keep unchanged the ZAMS color at M$_v$=6. Now one finds that a much larger value of ΔY/ΔZ (of the order of 7 around the solar metallicity) would be required in order to avoid a broadening of MS with Z, showing the additional contribution of model atmospheres to the spread of visual magnitudes. Such a result appears in agreement with the already quoted Pagel & Portinari (1998) finding, for which ΔY/ΔZ = 6 is still not sufficient for avoiding the spread.

As a final point, one may explore the rather popular assumption that the galactic enrichment follows a linear relation between Y and Z, adopting Z=0.0001 Y=0.23 for metal poor stars and Z=0.02, Y=0.27 for the sun, so that $\Delta Y/\Delta Z \sim 2$. In Fig. 4 we make use of our predictions under the above quoted assumption to repeat the analysis given by Pagel & Portinari (1998) for Hipparcos MS nearby stars. One finds that the predicted spread appear in fair agreement with observations. This is not a surprising result, since Pagel and Portinari already found a reasonable agreement for the rather large range of values $\Delta Y/\Delta Z$ = 3 $\pm$2. One finds also several concordances concerning the relation between the visual magnitude (at fixed temperature) and metallicity. However, it is difficult to go deeper in such a discussion, owing to the rather large uncertainties still existing in the observational sample.

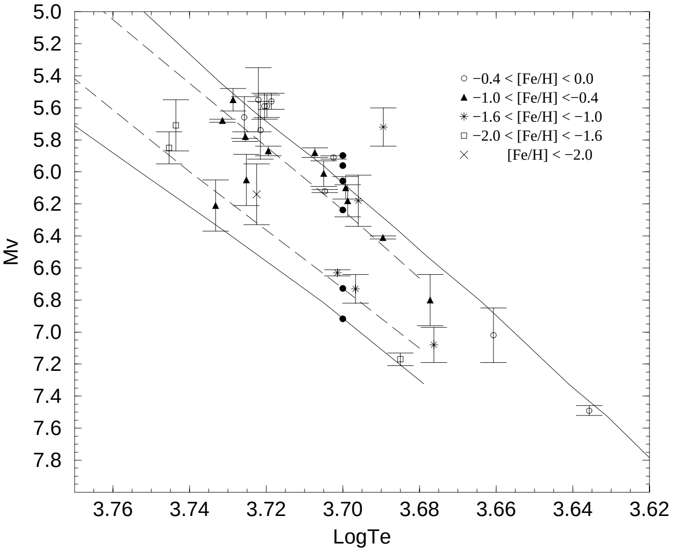

Fig. 4. Hipparcos data for stars with Z$\leq$0.02 in the M$_v$-logT$_{eff}$ plane (from Pagel & Portinari 1998) compared with our theoretical ZAMS with $\Delta Y/\Delta Z$ = 2, see text. The accuracy on the temperature observational data is assumed to be $\pm$ 50 K (see Pagel & Portinari 1998). The continuous lines are our theoretical ZAMS for Z=0.02, Y=0.27 (upper line) and Z=0.0001, Y=0.23 (lower line), whereas the dashed lines give the ZAMS for Z=0.01 Y=0.25 (upper line) and Z=0.001, Y=0.232 (lower line). Black dots show the predicted magnitudes at logT$_{eff}$= 3.70 for the above quoted composition and (at the larger luminosities) for the two suprasolar compositions Z = 0.03, Y=0.29; Z=0.04, Y= 0.31.

4. Conclusions

We have investigated the theoretical scenario for ZAMS stars with different chemical compositions, providing analytical relations connecting the MS location to Y and Z. We show that the assumption of no MS broadening for $\Delta Y/\Delta Z = 5$ is supported by theory only for the behavior of bolometric magnitudes. On the contrary, we find that the no-broadening condition can be reached in the observational M_{v},B-V plane only if $\Delta Y/\Delta Z \simeq 7$.

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