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Atomic diffusion in metal poor stars

The influence on the Main Sequence fitting distance scale, subdwarfs ages and the value of $\Delta Y/\Delta Z$

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Abstract. The effect of atomic diffusion on the Main Sequence (MS) of metal-poor low mass stars is investigated. Since diffusion alters the stellar surface chemical abundances with respect to their initial values, one must ensure – by calibrating the initial chemical composition of the theoretical models – that the surface abundances of the models match the observed ones of the stellar population under scrutiny. When properly calibrated, our models with diffusion reproduce well within the errors the Hertzsprung-Russell diagram of Hipparcos subdwarfs with empirically determined $T_{\rm eff}$ values and high resolution spectroscopical [Fe/H] determinations.

Since the observed surface abundances of subdwarfs are different from the initial ones due to the effect of diffusion, while the globular clusters stellar abundances are measured in Red Giants, which have practically recovered their initial abundances after the dredge-up, the isochrones to be employed for studying globular clusters and Halo subdwarfs with the same observational value of [Fe/H] are different and do not coincide. This is at odds with the basic assumption of the MS-fitting technique for distance determinations. However, the use of the rather large sample of Hipparcos lower MS subdwarfs with accurate parallaxes keeps at minimum the effect of these differences, for two reasons. First, it is possible to use subdwarfs with observed [Fe/H] values close to the cluster one; this minimizes the colour corrections (which are derived from the isochrones) needed to reduce all the subdwarfs to a mono-metallicity sequence having the same [Fe/H] than the cluster. Second, one can employ objects sufficiently faint so that the differences between the subdwarfs and cluster MS with the same observed value of [Fe/H] are small (they increase for increasing luminosity). We find therefore that the distances based on standard isochrones are basically unaltered when diffusion is taken properly into account.

On the other hand, the absolute ages, the age dispersion, the age-metallicity relation for Halo subdwarfs, as well as the value of the helium enrichment ratio $\Delta Y/\Delta Z$ obtained from the width of the empirical Halo subdwarfs MS, are all significantly modified when the properly calibrated isochrones with diffusion are used.

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1. Introduction

Atomic diffusion is a basic physical element transport mechanism usually neglected in standard stellar models. It is driven by pressure gradients (or gravity), temperature gradients and composition gradients. Gravity and temperature gradients tend to concentrate the heavier elements toward the center of the star, while concentration gradients oppose the above processes. Overall diffusion acts very slowly in stars, with time scales of the order of 10^9 years, so that the only evolutionary phases where diffusion is efficient are Main Sequence (but see also Michaud et al. 1983 for a discussion about the effect of diffusion in hot Horizontal Branch stars) and the White Dwarf cooling.

The occurrence of diffusion in the Sun has been recently demonstrated by helioseismic studies (see, e.g, Christensen-Dalsgaard et al. 1993; Guenther et al. 1996). Solar models including this process can reproduce much better than standard models the solar pulsation spectrum and the helioseismic values of helium surface abundance and depth of the convective envelope. Moreover, it seems that neither turbulence nor other hydrodynamical mixing processes substantially reduce the full efficiency of element diffusion in the Sun, otherwise the helioseismic constraints could not be satisfied (Richard et al. 1996). Since the Sun is a typical Main Sequence (MS) star whose structure closely resembles the one of metal poor MS objects, it appears likely that diffusion should also occur in MS globular cluster (GC) and field Halo stars and be as efficient as in the Sun. Very recently, Lebreton et al. (1999) have shown that diffusion is necessary for reproducing the effective temperatures of Hipparcos subdwarfs in the metallicity range $-1.0 \leq$[Fe/H]≤ -0.3, belonging mainly to the thick disk of the Galaxy. On the other hand the occurrence of a full efficiency of this process in Halo stars is still a matter of debate, since it appears to be unable to explain the near constancy of the ^{7}Li abundances in metal-poor stars with $T_{\rm eff}$ larger than $\sim$6000 K (see, e.g., Vauclair

& Charbonnel 1998). As reviewed by Vandenberg et al. (1996), turbulent mixing below the convective zone, rotation, mass loss, have been proposed as additional processes able to partially inhibit atomic diffusion; mass loss in particular (mass loss rates at the level of $\approx 10^{-12}$–$10^{-13} M_{\odot} yr^{-1}$ would be necessary to reproduce the observations) is an interesting candidate (Swenson 1995; Vauclair & Charbonnel 1995), but there are no strong observational constraints at present.

Investigations dealing with the effect of diffusion on Population II stars – and the present work goes along the same line – have generally considered a full efficiency of this process (but see also Proffitt & Michaud 1991), and their results can be regarded as an estimate of the upper limit of the effect of atomic diffusion on the Halo stars evolution (another non-conventional transport mechanism, radiative acceleration, does not appear to appreciably affect the evolutionary properties of low mass stars, at least in the range 1.1 $\leq M/M_{\odot} \leq$ 1.3, as investigated by Turcotte et al. 1998).

Due to diffusion (see, e.g., Castellani et al. 1997; Weiss & Schlattl 1999) the stellar surface metallicity and helium content progressively decrease during the MS phase – due to their sinking below the boundary of the convective envelope –, reaching a minimum around the Turn-Off (TO) stage; then, since envelope convection deepens, a large part of the metals and helium diffused toward the center are again engulfed in the convective envelope, thus restoring the surface Z (with Z we indicate, as usual, the mass fraction of the metals) to almost the initial value and Y (helium mass fraction), after the first dredge up, to a value almost as high as for evolution without diffusion. Along the Red Giant Branch (RGB) phase diffusion is basically inefficient because of the much shorter evolutionary time scales. The net effect on the evolutionary tracks is to have the MS (for a given stellar mass and initial chemical composition) colder for fixed value of the luminosity, and a less luminous and colder TO (which is reached earlier), with respect to standard models. The reason for this behaviour is that the inward settling of helium raises the core molecular weight and the molecular weight gradient between surface and center of the star. This increases the stellar radius and the rate of energy generation in the center. The metal diffusion only partially counterbalances this effect by decreasing the opacity in the envelope and increasing the central CNO abundance.

With respect to a standard isochrone of given initial metallicity and reference TO luminosity, isochrones computed accounting for the diffusion of helium and metals give an age lower by $\simeq$1 Gyr, if the same initial metallicity is used. As far as the RGB evolution is concerned, the location of the RGB in the Hertzsprung-Russell (HR) diagram is basically unchanged with respect to standard models, and the level of the Horizontal Branch is also almost negligibly affected (Castellani et al. 1997).

Several papers have been published about the influence of atomic diffusion in old stars (see, e.g., Proffitt & Vandenberg 1991; Chaboyer et al. 1992; D'Antona et al. 1997; Castellani et al. 1997; Cassisi et al. 1998; Castellani & Degl'Innocenti 1999), with the main goal of studying the influence on GC ages. The approach usually followed is to compute models with diffusion for a certain set of initial metallicities, and then to compare with the observational Colour-Magnitude-Diagram (CMD) of a given GC the isochrones whose initial metal content matches the spectroscopical GC one. Since the chemical composition of a GC is determined by means of observations of its RGB stars (see, e.g., Carretta & Gratton 1997), the spectroscopical GC metallicity truly reflects the initial one.

A very different situation holds for field MS subdwarfs, a point recently raised by Morel & Baglin (1999 - hereinafter MB99). The spectroscopical subdwarfs metallicity is not the original one, because diffusion along the MS decreases the envelope metallicity (and helium content). When comparing theoretical diffusive isochrones with subdwarfs, one must compute models with suitable initial chemical abundances which produce, at the subdwarf age, its observed surface metallicity. This means that subdwarfs models must be computed using a larger initial Z with respect to the observed one, the exact value depending on the star age. This occurrence has potentially very important implications for example for MS-fitting distances and subdwarfs GC ages, since it implies that the MS (and TO) of subdwarfs and GC sharing the same observational value of the metallicity are not coincident.

In this paper we present models for the MS phase of low mass metal-poor stars, accounting for atomic diffusion (Sect. 2); we have considered the full efficiency of this process, as in the Sun. We will then analyze for the first time in a consistent way the effect of diffusion on three important quantities for cosmological and Galactic evolution models, namely GC distances derived by means of the MS-fitting technique (Sect. 3), age of field subdwarfs (Sect. 4), and the helium enrichment ratio $\Delta Y/\Delta Z$ estimated from the width of the local subdwarfs MS (Sect. 5). A summary follows in the final section. In view of the previously discussed possibility that the efficiency of diffusion could be somewhat reduced in Population II stars, our results may be viewed as upper limits.

2. The models

The stellar evolution computations have been performed using the same code and the same input physics as in Salaris & Weiss (1998 - hereinafter SW98). We just recall that we have used the opacities by Iglesias & Rogers (1996) and Alexander & Ferguson (1994) for an α-enhanced heavy elements mixture ($\langle[\alpha/\mathrm{Fe}]\rangle$=0.4; the details of the distribution are given in SW98), and that the mixing length calibration allows to reproduce the RGB effective temperatures of a selected sample of GC in the ($M_{\mathrm{bol}}, T_{\mathrm{eff}}$) plane, as derived by Frogel et al. (1983), which is the observational constraint for Halo stars. In case of models with diffusion, since the RGB position is almost unchanged with respect to standard isochrones, the same mixing length value satisfies the metal-poor RGB observational constraint. Therefore, we did not change the mixing length calibration with respect to the case of standard isochrones. This permits also to clearly show the influence of diffusion on the stellar models without any contribution from the variation of other parameters. We stress

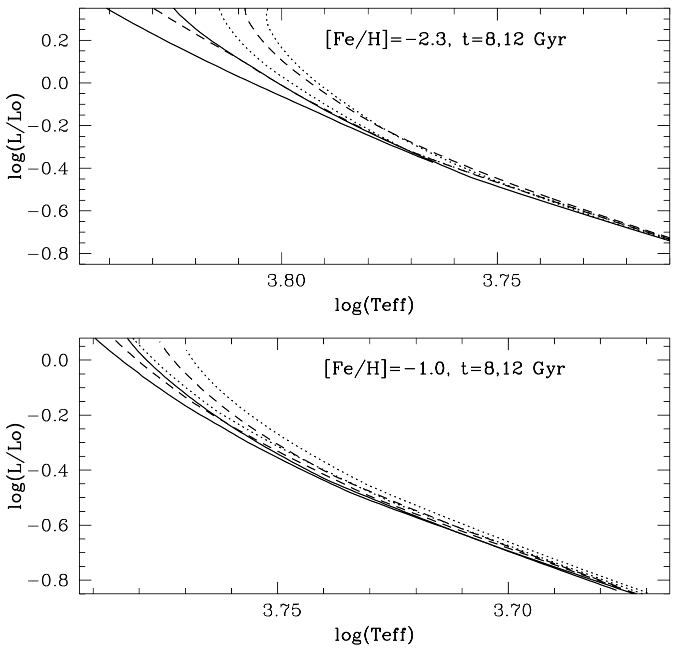

Fig. 1. HR diagram of standard (solid line), D (see text - dashed line) and C isochrones (see text - dotted line) with t =8,12 Gyr, [Fe/H]=-2.3 (upper panel) and [Fe/H]=-1.0 (bottom panel).

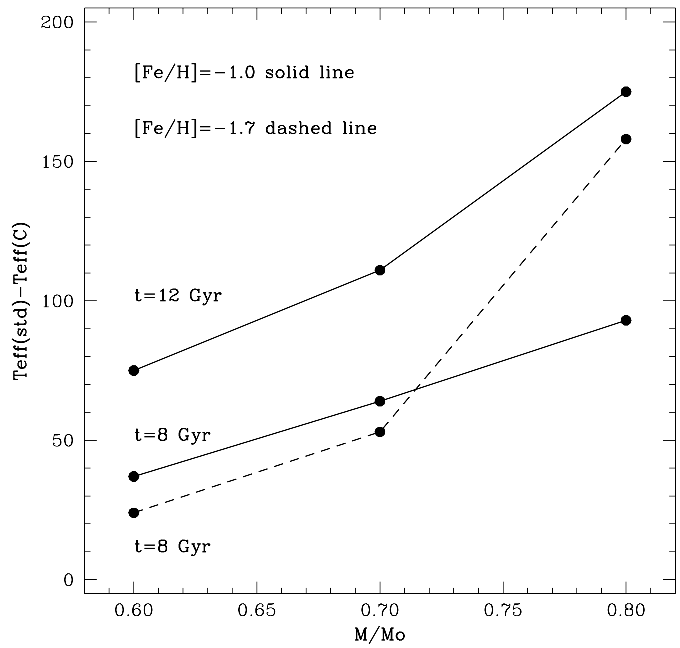

Fig. 2. Difference $\Delta T_{\rm eff}$ (K) between standard and calibrated diffusive C isochrones for three selected values of the evolving mass, with metallicities [Fe/H]=-1.0 (t =8 and 12 Gyr) and -1.7 (t =8 Gyr). The crossing between the [Fe/H]=-1.7 models and the more metal rich ones is due to evolutionary effects.

also that large part of our results does not depend on the mixing length calibration.

For the present calculations we have included the diffusion of helium and heavy elements following Thoul et al. (1994); their formalism and the input physics used in our models have been already successfully tested on the Sun (see, e.g., Ciacio et al. 1997). The variations of the abundances of H, He, C, N, O and Fe are followed all along the structures; all other elements are assumed to diffuse in the same way as fully-ionized iron (see, e.g., Thoul et al. 1994 for a comparison among different diffusion formalisms). The local changes of metal abundance are taken into account also in the opacity computation, by calculating the actual global metallicity at each mesh point, and then interpolating among tables with different Z. In this way one does not take into account the small changes in the metal distribution due to differences in the diffusion velocities of C,N,O and Fe; however, for the mass range we are dealing with ($M \leq$1.0 $M_{\odot}$) the differences are small and our procedure does not introduce any significant error in the opacity (see, e.g., the detailed discussion in Turcotte et al. 1998).

We have computed a set of MS models (and isochrones) with diffusion and initial metallicities [Fe/H]=-2.3, -2.0, -1.7, -1.3, -1.0, -0.7, -0.6 (Y_0=0.23 and $\Delta Y/\Delta Z$=3 as in SW98). In addition we have also computed a set of isochrones for 8 and 12 Gyr which displays as actual surface metallicity the set of values previously given (we will call them 'calibrated' diffusive isochrones, following the nomenclature by MB99). When computing the latter isochrones we had to ensure that, for the selected ages, all the different evolving masses showed the prescribed surface metallicity. This means that we had to employ an iterative procedure for finding the exact value of the initial metallicity (larger than the final one) to be used for each case (we kept fixed $\Delta Y/\Delta Z$=3 when deriving the initial helium abundance).

In Fig. 1 we show a comparison in the HR diagram among the sets of isochrones computed, and the standard ones by SW98, with t =8 and 12 Gyr and [Fe/H]=-2.3 and -1.0. For the standard (solid lines) and 'calibrated' diffusive ones (dotted lines - hereinafter C) the labelled value of [Fe/H] represents the actual surface metallicity, which is constant along the isochrone, while for the non calibrated isochrones with diffusion (dashed line - hereinafter D) it represents only the initial surface metallicity.

Our results closely resemble the results by MB99; specifically, for a fixed age and luminosity the standard isochrones are hotter than the D and C ones. The C isochrones are the reddest among the three sets. The $T_{\rm eff}$ difference at fixed luminosity among the three sets of isochrones increases with increasing metallicity. As in MB99 we find that the shift toward higher $T_{\rm eff}$ of the C isochrones with respect to the standard ones increases for increasing luminosities; this changes slightly the slope of the MS, making it more vertical for the C isochrones. At [Fe/H]=-2.3 the C and D isochrones are almost coincident all along the lower MS. Table 1 displays a quantitative evaluation of the $T_{\rm eff}$ difference, at selected luminosities along the lower MS, between standard and C isochrones with t=8 and 12 Gyr and metallicities [Fe/H]=-1.0, -1.7, -2.3.

Fig. 2 shows the difference $\Delta T_{\rm eff}$ at fixed age between standard and C isochrones for three selected values of the evolving mass along the MS, metallicities [Fe/H]=-1.0 and -1.7, t =8

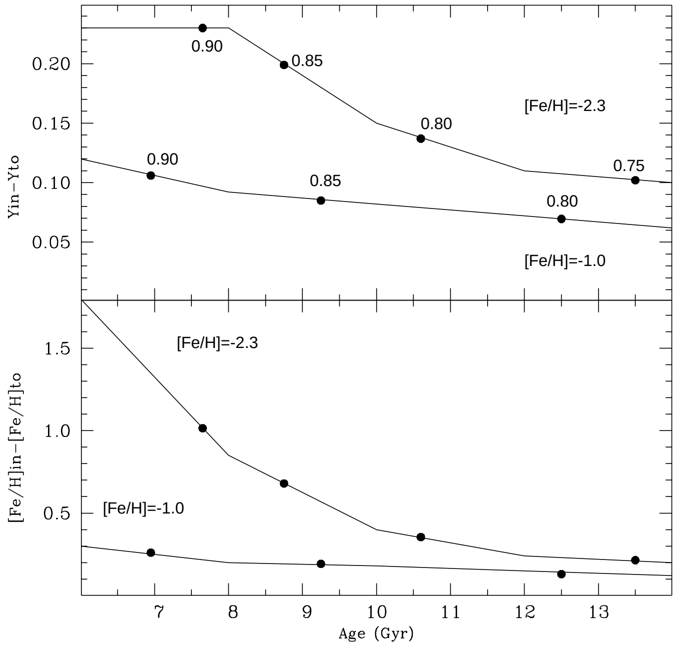

Fig. 3. He and metal depletion at the TO (difference between the initial and the TO values) as a function of the age for selected D isochrones with the displayed initial metallicities. Filled circles show selected TO masses indicated in units of $M_{\odot}$ (upper panel).

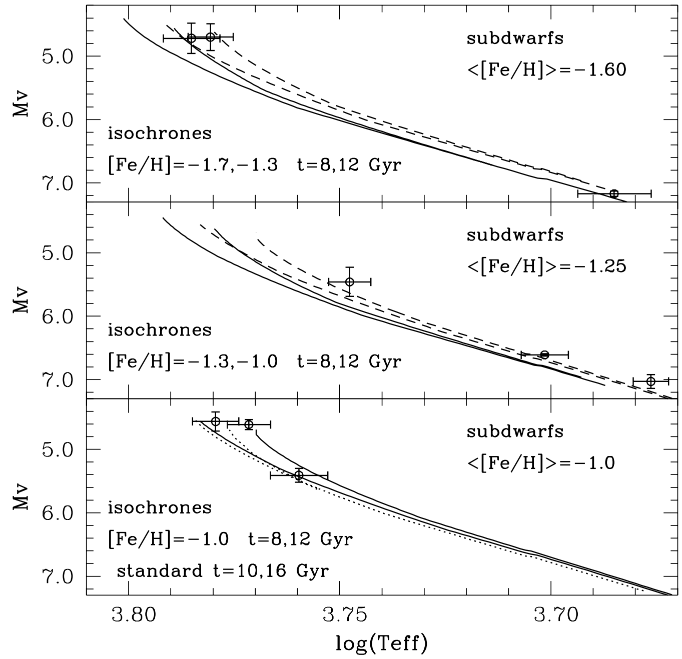

Fig. 4. $M_{\rm V}$-$T_{\rm eff}$ diagram of C isochrones and a sample of subdwarfs with accurate Hipparcos parallaxes and IRFM effective temperatures. The average subdwarfs metallicity is given in the labels at the top right corner of the three panels; isochrones metallicities and ages are shown at the left bottom corner of each panel. Subdwarfs are represented by circles; error bars on their values of M_V and log($T_{\rm eff}$) are also displayed. In the upper and middle panel solid lines correspond to the C isochrones with the lower metallicity between the given values. In the bottom panel C isochrones are represented with solid lines, while the standard isochrones with [Fe/H]=-1.0 and t=10,16 Gyr are also displayed (dotted lines) for comparisons.

Table 1. $T_{\rm eff}$ difference (in K) between standard and C isochrones ($T_{\rm eff}$(standard)-$T_{\rm eff}$(C)) for three selected metallicities ([Fe/H]=-2.3, -1.7, -1.0) and three luminosities along the lower MS.

	t=8 Gyr			t=12 Gyr		
$\log(L/L_{\odot})$	-2.3	-1.7	-1.0	-2.3	-1.7	-1.0
-0.4	37	48	64	47	65	90
-0.6	29	40	52	37	54	76
-0.8	20	30	41	28	45	63

and 12 Gyr. For the [Fe/H]=-1.7 isochrones only data with $t=$8 Gyr are shown, since stars with M=0.8$M_{\odot}$ are evolved off the MS at $t=$12 Gyr. The displayed data are comparable with analogous quantities in Fig. 6 of MB99; our results appear consistent with MB99, when taking into account that their $\Delta T_{\rm eff}$ values correspond to an age of 10 Gyr.

In Fig. 3 the differences Δ[Fe/H] (ΔY) between the initial metallicity (helium content) and the TO surface values of D isochrones are displayed for two selected initial metallicities and various ages. As a general trend, Δ[Fe/H] and ΔY increase for decreasing age (in the age range we are dealing with) and for decreasing initial metallicity (at fixed age). In the age range 6-14 Gyr Δ[Fe/H] is generally between 0.1 and 1.0 – apart for the most metal poor isochrones which show a larger metal depletion (Δ[Fe/H]$\simeq$1.8 at t=6 Gyr for an initial [Fe/H]=-2.3) –, while ΔY ranges between $\sim$0.05 and $\sim$0.2; the surface Y is practically zero for the [Fe/H]=-2.3 isochrones when t is less than about 8 Gyr.

This increase of the TO surface metallicity (and helium) depletion with decreasing age could appear at first surprising, since diffusion has less time to work when age is lower; however, one must also take into account that convective envelopes are progressively thinner for stars populating the TO at decreasing age, thus increasing the rate of depletion of helium and metals (notice that more metal poor models have thinner surface convective regions). It is the competition between these two factors which determines the final trend of the TO surface abundances with time.

In Fig. 4 we compare our C isochrones (bolometric luminosities were transformed to $M_{\rm V}$ using the bolometric corrections described in Weiss & Salaris 1999; we just recall that, after the necessary calibration of the zero point to reproduce the solar $M_{\rm V}$ value, our adopted bolometric corrections from Buser & Kurucz 1978, 1992 agree quite well with the empirical determinations by Alonso et al. 1996a) with a sample of metal-poor subdwarfs with accurate Hipparcos parallaxes ($\sigma(\pi)/\pi < 0.12$) listed by Carretta et al. (1999), and $T_{\rm eff}$ derived from the Infrared Flux Method (IRFM – Alonso et al. 1996b). The goal is to check if isochrones with full efficiency of diffusion are compatible with the HR diagram of field subdwarfs with accurate parallaxes and empirical $T_{\rm eff}$ determinations (therefore eliminating the influence of the adopted colour-transformations).

Lebreton et al. (1999) recently performed this kind of comparison for subdwarfs with metallicities in the range $-1.0<$[Fe/H]<0.3, and found that for $-1.0<$[Fe/H]<-0.5 the inclusion of the full efficiency of diffusion is necessary for reproducing observational data. We extend their analysis by studying the case of lower metallicities. Our adopted subdwarfs spectroscopic [Fe/H] values come from Carretta et al. (1999), and are homogeneous with the Carretta & Gratton (1997) metallicity scale for GC; even if the metallicities adopted by Alonso et al. (1996b) for applying the IRFM method are different (generally lower by ≈ 0.2), the sensitivity of the derived $T_{\rm eff}$ to the input metallicity is so low (Alonso et al. 1996b) that no appreciable inconsistency is introduced by our choice of the [Fe/H] scale. For two stars we found differences as high as ≈1.0 between the metallicity used by Alonso et al. (1996b) and the Carretta et al. (1999), and we did not consider them. The [Fe/H] values for the subdwarfs displayed in the pictures are in the ranges, respectively, between -1.55 and -1.69 (top panel), -1.24 and -1.28 (middle panel), -0.98 and -1.02 (bottom panel). The error bar on [Fe/H] is typically by 0.10-0.15, while the errors on $T_{\rm eff}$ and $M_{\rm V}$ are shown in the figure.

The displayed MS isochrones have ages equal to 8 and 12 Gyr respectively, corresponding to approximately the upper and lower limit of the ages determined by SW98 for a large sample of Galactic GC. As it is evident from the figure, the agreement between observations and theoretical models is satisfactory. Our calibrated diffusive C isochrones (which are the correct ones to be compared with field subdwarfs of a given metallicity) reproduce satisfactorily the observations. The best agreement is for subdwarfs with average metallicity [Fe/H]=-1.0 and -1.6; at the intermediate metallicity -1.25 the models appear to be slightly too hot, but when taking into account the error bar on the temperature and metallicity of the subdwarfs the discrepancy does not appear to be significant. In the case of [Fe/H]=-1.0 standard isochrones are also shown; it is clear that in spite of the good agreement between C models and data, one cannot use these results as a definitive proof that diffusion is fully efficient in Halo subdwarfs. Standard isochrones can also reasonably reproduce the observational data (even if for different ages), at least given the present sample of objects and observational uncertainties on $M_{\rm V}$ and $T_{\rm eff}$.

Regarding this last point one should notice that Cayrel et al. (1997) have shown how the MS location of standard isochrones appears to be too hot by ≈120-140 K in comparison with a sample of metal poor subdwarfs with accurate Hipparcos parallaxes, when using the empirical $T_{\rm eff}$ determinations by Alonso et al. (1996b), and [Fe/H] values from the compilations by Cayrel de Strobel et al. (1997). This difference with respect to our conclusion that at [Fe/H]=-1.0 standard isochrones are still able to reproduce within the errors the position of local subdwarfs, is due mainly to the different [Fe/H] scale we have employed. We used the Carretta et al. (1999) metallicities which are on a scale homogeneous with the GC metallicities we will use in the next section. For the stars with [Fe/H]~ -1.0 our adopted [Fe/H] values are about 0.2-0.3 larger than the corresponding values given by Cayrel de Strobel et al. (1997 - we averaged the high S/N data); these larger metallicities reduce the discrepancy between standard isochrones and observations.

3. Atomic diffusion and MS-fitting distances

The MS-fitting technique is the 'classical' method to derive distances to GC (see, e.g., Sandage 1970). The basic idea is very simple. Suppose that precise parallaxes of neighbouring subdwarfs are available; for a given GC metallicity $Z_{\rm cl}$, it is possible to construct an empirical template MS by considering subdwarfs with metallicity $Z_{\rm sbdw}$ close to $Z_{\rm cl}$ and applying to their colours small shifts (obtained using the derivative $\Delta(colour)_{\rm MS}/\Delta$[Fe/H] as derived from theoretical isochrones) for reducing them to a mono-metallicity sequence with $Z = Z_{\rm cl}$. The fit of this empirical MS to the observed GC one (reddening-corrected) provides the cluster distance modulus.

The main underlying assumption is that the MS of subdwarfs with a certain value of [Fe/H] is coincident with the MS of GC with the same metallicity. If atomic diffusion is at work in Halo stars, the underlying assumption of this technique is no longer rigorously satisfied. The point is that (as previously discussed) the spectroscopical metallicity of a GC is determined from its RGB stars; this metallicity is very close to the primordial GC chemical composition, but is not (due to the effect of diffusion) the MS one. Therefore, when fitting the local subdwarfs MS to the MS of a GC with the same observed metallicity, one is introducing an error in the derived distance modulus.

The release of the Hipparcos catalogue has enlarged the number of metal poor subdwarfs with precise parallaxes which can be now used for applying this technique to the Galactic GC, and several authors (see, e.g, Reid 1997; Gratton et al. 1997; Chaboyer et al. 1998; Carretta et al. 1999) have recently derived distances (and ages) of GC using the MS-fitting and subdwarfs with Hipparcos parallaxes. In particular, Carretta et al. (1999) have carefully analyzed the total error budget associated with the MS-fitting, but the effect of atomic diffusion in subdwarfs is nowhere mentioned.

We display in Fig. 5 standard, C and D isochrones transformed to the $M_{\rm V}-(B-V)$ plane according to the transformations described in Weiss & Salaris (1999), for [Fe/H]=-2.3 and -1.0. In the case of D isochrones, when computing the bolometric corrections (already used in the previous section) and the $T_{\rm eff}$-colour conversion, we have taken into account the fact that the surface [Fe/H] value is not constant along the MS (it is actually decreasing). It must be noticed that the surface helium content for stars around the TO of the isochrones with diffusion is always much lower (generally Y is in the range ≈0.1-0.2 for ages between 8 and 12 Gyr, as discussed in the previous section) than the helium content used in the model atmospheres producing the adopted colour transformations. However, this does not introduce a substantial systematic error since, according to Carney (1981), the He abundance does not appreciably affect the flux distribution at temperatures appropriate to GC dwarfs and subgiants.

The behaviour of the isochrones in the observational $M_{\rm V}-(B-V)$ plane closely follows the results in the theoretical

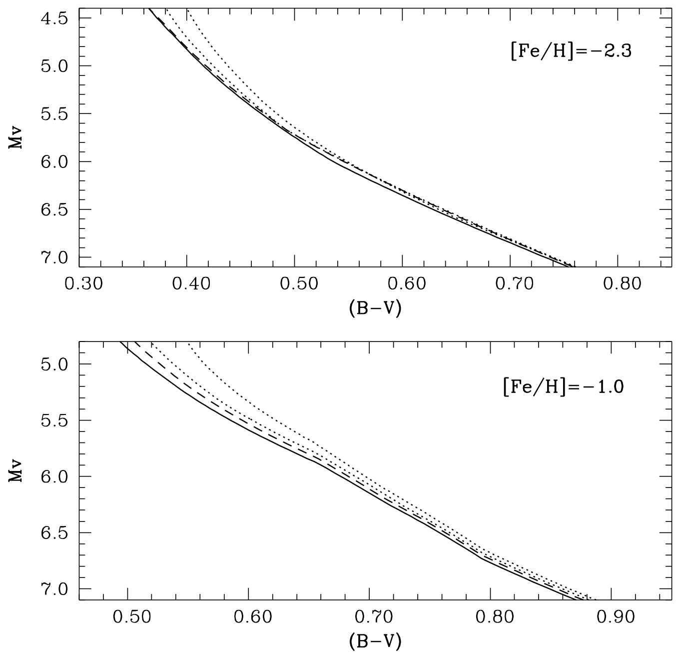

Fig. 5. Colour Magnitude Diagram of standard (solid line) and D (dashed line) isochrones with t =8 Gyr and the displayed metallicities; also plotted are C isochrones (dotted lines) for the same metallicities but t =8 and 12 Gyr.

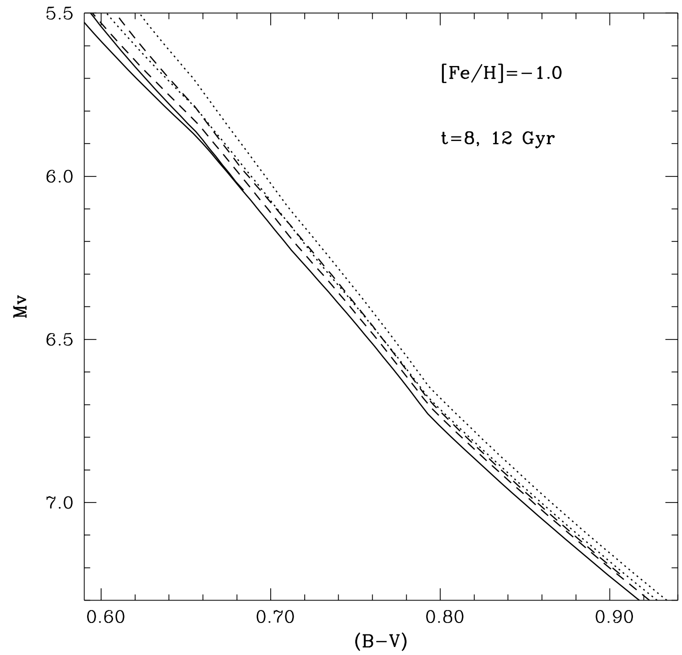

Fig. 6. Colour Magnitude Diagram of the low MS of standard (solid line), D (dashed line) and C isochrones (dotted lines) with t =8 and 12 Gyr and [Fe/H]=-1.0.

HR diagram. Standard isochrones (solid line) are systematically bluer than the diffusive ones. The C isochrones are the reddest ones, and they are progressively redder than the standard or the D ones for increasing age (the effect is stronger for large metallicities). In Fig. 6 the lower MS for [Fe/H]=-1.0 and t =8,12 Gyr is shown; when $M_{\rm V}$ $\leq$6 standard isochrones are unaffected by age (a fact that is well known), while D isochrones are insensitive to the age only for $M_{\rm V}$ $\leq$7 and C isochrones are always affected by the age, at least down to $M_{\rm V}$=7.3 (because of the metal decrease with time due to diffusion).

The MS of a GC with an observed RGB metallicity [Fe/H]=-1.0 is given by the D isochrones in Fig. 6, while the MS of local subdwarfs with the same observed metallicity is given by the C isochrones. As it is evident the two MS are generally not coincident.

Another difference with respect to the standard case (and another potential source of systematic errors on the actual MS-fitting distances) is the value of the derivative $\Delta(B-V)_{\rm MS}/\Delta$ [Fe/H]. This is the only information needed from theoretical isochrones to be employed in the MS-fitting technique; it is used for shifting the subdwarfs to a mono-metallicity sequence corresponding to the observed cluster [Fe/H]. Since the difference in colour between the standard MS and the C MS depends on the metallicity (see Fig. 5) this will have an impact on $\Delta(B-V)_{\rm MS}/\Delta$[Fe/H] for the subdwarfs.

Are these differences large enough to affect substantially the MS-fitting GC distances? It depends on the subdwarf sample. To explain this point let's consider, as an example, subdwarfs with [Fe/H]$\simeq -1.3$ and $M_{\rm V} \simeq 6$, which hypothetically have to be employed for deriving the distance to a GC with [Fe/H]$\simeq -0.7$. The variation of $\Delta(B-V)_{\rm MS}/\Delta$[Fe/H] due to diffusion causes a shift of the empirical subdwarfs MS at the cluster metallicity by $\Delta(B-V)$ $\simeq$+0.02 with respect to the standard case. This, by itself, would induce a GC distance modulus larger by $\simeq$0.1 mag, since the MS slope $\Delta M_{\rm V}/\Delta(B-V)$ is equal to about 5.5. However, one must correct for the vertical $M_{\rm V}$ difference between subdwarfs and GC MS, which tends to reduce the derived distance modulus by $\approx$0.05–0.08 mag in the age range 8–12 Gyr. The final combined effect is to have distances unchanged or increased at most by 0.05 mag with respect to the standard case. However, in the hypothesis that for determining the MS-fitting distance to a GC with [Fe/H]$\simeq -1.3$ one can use only subdwarfs with [Fe/H]$\simeq -0.7$, the situation is quite different, since the use of the diffusive C isochrones would cause a decrease of the distance modulus by $\approx$0.10-0.13 mag.

In the following we will study the effect of diffusion on the MS-fitting distances obtained using subdwarfs with accurate Hipparcos parallaxes. We have considered, as a test (the results are summarised in Table 2), four clusters included in the analysis by Gratton et al. (1997), namely M92 ([Fe/H]$\simeq -2.15$), M5 and NGC288 ([Fe/H]$\simeq -1.1$), 47Tuc ([Fe/H]$\simeq -0.7$). The subdwarfs $M_{\rm V}$, $(B-V)_0$ and [Fe/H] values come from Table 2 of Gratton et al. (1997); the clusters reddenings and metallicities are from the quoted paper, as well as the observational clusters MS lines. For each cluster we have considered only bona fide single stars fainter than V=6 (to avoid evolutionary effects for the standard isochrones, as well as the influence of the mixing-length calibration), with $\sigma(\pi)/\pi < 0.12$ and in the same metallicity range as in Gratton et al. (1997).

In the case of the standard models by SW98 we recover basically the same distances by Gratton et al (1997), whose results

Table 2. MS-fitting distance moduli ($(m-M)_V$) of selected clusters.

		$t_{\rm cl}$=8Gyr		$t_{\rm cl}$=12Gyr	
Cluster	standard	$t_{\rm sbdw}$=8 Gyr	$t_{\rm sbdw}$=12 Gyr	$t_{\rm sbdw}$=8 Gyr	$t_{\rm sbdw}$=12 Gyr
M92	14.76±0.04	14.75±0.04	14.74±0.04	14.75±0.04	14.74±0.04
M5	14.59±0.03	14.56±0.03	14.53±0.03	14.58±0.03	14.54±0.03
NGC288	14.93±0.03	14.90±0.03	14.88±0.03	14.92±0.03	14.89±0.03
47 Tuc	13.58±0.04	13.59±0.04	13.56±0.04	13.63±0.04	13.59±0.04

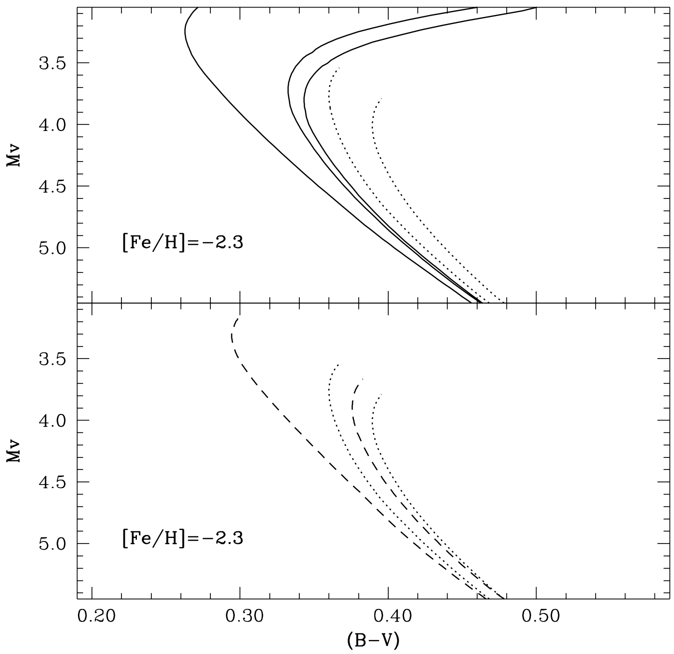

Fig. 7. Upper panel: Colour Magnitude Diagram of the TO region of standard (solid lines) and C isochrones (dotted lines) for the displayed value of [Fe/H]; the ages are 8,12,13 Gyr for the standard isochrones, 8 and 12 Gyr for the C ones. Lower panel: as in the upper panel, but for D (dashed lines) and C (dotted lines) isochrones with t =8,12 Gyr.

were obtained by using a value for $\Delta(B-V)_{\rm MS}/\Delta$ [Fe/H] derived from different isochrones, and considering subdwarfs also in the range 5.5< $M_{\rm V}$ <6.0. When deriving the MS-fitting distances taking into account diffusion, we have (as outlined in the previous example) corrected the subdwarfs colours by using the $\Delta(B-V)_{\rm MS}/\Delta$ [Fe/H] values derived from the C models, and we have also accounted for the difference in brightness at fixed colour between the subdwarfs MS (C isochrones) and the clusters one (D isochrones). Since there are small evolutionary effects for the D isochrones (representing the GC) even when 6≤ $M_{\rm V}$ ≤7, we have taken into account 4 different possibilities. In the first two cases we have assumed for the clusters age $t_{\rm cl}$=8 Gyr with subdwarfs ages $t_{\rm sbdw}$=8 and 12 Gyr, and in the second two cases we considered $t_{\rm cl}$=12 Gyr and again $t_{\rm sbdw}$=8 and 12 Gyr.

As it is clear from Table 2, there are no appreciable modifications to the distance moduli derived from standard isochrones. The differences with respect to the standard case are small and generally within the small formal error bars associated to the fit (the error bar takes into account *only* the error on the fit due to the uncertainties on the subdwarfs $M_{\rm V}$ and $(B-V)$). This is a quite important point, since it confirms the robustness of the published Hipparcos MS-fitting distances which did not take into account the effect of atomic diffusion on GC and field subdwarfs evolution.

The reason for this occurrence is that – thanks to the Hipparcos results – the sample of lower MS metal poor subdwarfs with accurate parallaxes has substantially increased with respect to the recent past. In performing the MS fitting we have used objects whose metallicity is close to the actual GC metallicity; in this case, as it is evident, the colour correction to be applied to the subdwarfs is small, and even the occurrence of a sizeable change of $\Delta(B-V)_{\rm MS}/\Delta$ [Fe/H] does not modify appreciably the final distance. Moreover, the subdwarfs are all sufficiently faint so that the difference between the GC (D isochrones) and subdwarfs (C isochrones) MS is generally kept at the lowest possible value (this difference generally increases for increasing luminosity).

In conclusion, the effect of diffusion on the two main distance determination methods for GC stars, namely MS-fitting and HB fitting, is practically negligible, since also the HB luminosities are negligibly influenced by diffusion. The final effect on the GC age estimates is therefore just a reduction by about 1 Gyr due to the change of the TO brightness.

4. Atomic diffusion and subdwarfs ages

The age of field subdwarfs is, together with the age of stellar clusters, an important piece of information needed for understanding time scales and formation mechanism of the Galaxy. As repeatedly stressed before, the isochrones used for studying field subdwarfs of a certain surface metallicity are different from the ones to be employed when dealing with GC with the same observational value of [Fe/H]. This is clearly at odds with the usual procedure, when using standard isochrones, to use the same models for field and GC MS stars.

In Fig. 7 (upper panel) we display, as an example, standard and C isochrones with [Fe/H]=−2.3 and selected ages (t =8,12,13 Gyr in the case of standard models, while for C isochrones t =8,12 Gyr). It appears clear how the influence of diffusion is extremely relevant for the derived subdwarfs ages. The TO absolute V brightness for a standard isochrone with t =13 Gyr is coincident with the TO brightness of a C isochrone of only 8 Gyr; both the TO $M_{\rm V}$ and $(B-V)$ differences corresponding to an age between 8 and 12 Gyr are strongly reduced (by ≃50%) when passing from standard to C isochrones. This undoubtedly causes a strong reduction in the derived subdwarfs age, and has an important effect also on the determination of the age dispersion.

The reason for such a big difference with respect to standard calculations is that the C isochrone is basically an isochrone of much larger initial metal abundance than the standard one (by how much larger depends on the age) and with diffusion. It is well known that for a fixed age the effect of diffusion at a fixed initial metallicity is to decrease the TO luminosity (and colour); in the case of C isochrones, there is in addition the effect of the larger initial abundance which further lowers the TO luminosity (and colour); the amount of the cumulative effect depends on the selected age and initial metallicity.

In the lower panel of Fig. 7 a comparison between the TO region of C and D isochrones with [Fe/H]=-2.3 and t =8,12 Gyr is shown. The use of the D isochrones (suitable for GC) for deriving subdwarfs ages does not introduce a too large error for t =12 Gyr, while the difference with respect to C isochrones is very large for t =8 Gyr. This is due to the fact that, due to the lower age, the TO-mass is higher and therefore the depth of the convective envelope is smaller in TO stars, with the consequent larger depletion (and increase of the initial metallicity for the calibrated models) of the metal and helium abundances due to diffusion.

Diffusion has further important consequences when trying to determine the age-metallicity relation for old Halo subdwarfs. We have already seen that the use of diffusive C isochrones in place of standard ones strongly reduces the derived subdwarfs ages. Once the age of a sample of subdwarfs is obtained, one can study the age-metallicity relation for deriving information about Galactic formation mechanism and time scales. Of course the relevant quantity is the relation between the age of the stars and the metallicity from which they formed, which, in case of diffusion, is different from the actual one. The difference between initial and surface [Fe/H] at the TO is always within 0.1-0.3 for ages of about 10 Gyr or larger. But if one derives subdwarfs ages of the order of 6-8 Gyr (using the appropriate C isochrones), the observed [Fe/H] of TO stars must be increased by $\approx$0.2-1.0 (somewhat larger corrections are found for the most metal poor models with [Fe/H]=-2.3) for obtaining the initial value. This has to be taken into account in the analysis.

It is interesting to notice that if, for example, TO very metal poor subdwarfs with [Fe/H] around -3.0 (a sample of them can be found in Schuster et al. 1996) are found to be relatively young (t =8 Gyr) when employing the appropriate α-enhanced diffusive C isochrones, their initial metallicity had to be [Fe/H]$\simeq -2.2$, very similar to the initial metallicity of the most metal poor GC.

By considering the fact that the [Fe/H] depletion is larger at lower ages (at least for ages larger than $\approx$6 Gyr), it is interesting to notice that if one finds in a given observed metallicity range that metal poor subdwarfs are younger than metal rich ones, this could correspond – for a particular combination of ages and width of the metallicity range – to an age spread at a constant value of the initial metallicity.

5. Atomic diffusion and the value of $\Delta Y/\Delta Z$

The ratio $\Delta Y/\Delta Z$ of helium supplied to the interstellar medium by stars relative to their supply of heavy elements is an important quantity to test theoretical stellar yields and for deriving the slope of the relation between helium and oxygen in extragalactic HII regions, a fundamental ingredient for determining the primordial helium abundance.

One possible approach to the determination of this quantity is the study of the MS width of local subdwarfs. Since changes of the initial values of Y and Z push the MS in opposite directions (increasing Y makes the MS bluer, while increasing Z makes it redder), the width of the local subdwarfs MS for a fixed metallicity range is a function of the $\Delta Y/\Delta Z$ ratio in the interstellar medium. One can therefore consider two $\Delta Y/\Delta Z$ indicators: either the vertical (usually in $M_{\rm bol}$) width at a fixed value of $T_{\rm eff}$, or the horizontal width (in $(B-V)$ or log($T_{\rm eff}$)) at a fixed value of $M_{\rm V}$ (see, e.g., Castellani et al. 1999 and references therein). Usually the lower MS (corresponding to subdwarfs with $M_{\rm V} >$5.5-6.0) is used for the analysis to avoid (as in the MS-fitting technique) evolutionary effects and the influence of the mixing length calibration.

As it has been shown before, one of the effects of atomic diffusion on MS subdwarfs is to increase the MS width for a fixed metallicity interval and assumed initial $\Delta Y/\Delta Z$ value. This is due to the fact that the colour difference between the diffusive C isochrones and the standard ones is metallicity dependent, and is larger at larger metallicities.

As an example, we have considered a value for subdwarfs effective temperature log($T_{\rm eff}$)=3.70 (corresponding to $M_{\rm V} >$6); we then computed the MS $\Delta M_{\rm bol}$ broadening due to diffusion, in the interval between [Fe/H]=-2.3 and -0.7 – a metallicity range typical of Halo subdwarfs – and for subdwarfs ages equal to 8 and 12 Gyr, by means of comparisons with the SW98 models. As expected, $\Delta M_{\rm bol}$ results to be larger for C isochrones with respect to standard ones, the exact value depending on the subdwarfs age since the entire MS location of C isochrones does depend on age; this means that standard isochrones underestimate $\Delta Y/\Delta Z$ with respect to the calibrated diffusive ones.

The amount of this systematic difference was derived by computing additional C isochrones and varying the initial $\Delta Y/\Delta Z$ ratio in the range between 1 and 5. We found that C isochrones (in the explored $\Delta Y/\Delta Z$ range) lead to initial $\Delta Y/\Delta Z$ ratios larger by $\approx$1-2, the exact amount depending on the subdwarfs ages. Moreover, we found that the dependence on the initial helium abundance of the values of $M_{\rm bol}$ at a fixed $\log(T_{\rm eff})$ along the lower MS, is in broad agreement with the results from standard models by Castellani et al. (1999).

6. Summary

We have analyzed the influence of heavy elements and helium diffusion on the MS of metal poor low mass stars in connection with the determination of GC distances via MS-fitting technique, field subdwarfs ages, and the helium enrichment ratio $\Delta Y/\Delta Z$ derived from the width of the subdwarfs MS. These three quantities are all of paramount importance for cosmological and Galactic evolution issues.

The necessity of this analysis was prompted by the recognition that isochrones for MS subdwarfs and GC with direct spectroscopical determinations of the metallicity are not the same if diffusion is taken properly into account; moreover, differences in the MS location and TO position between subdwarfs standard and diffusive isochrones are metallicity and age dependent.

We have considered the full effect of atomic diffusion, without any allowance for possible hydrodynamical mixing phenomena which could reduce the efficiency of diffusion in Population II stars, as some observations appear to suggest (see the discussion in Sect. 1).

Our main results are:

i) α-enhanced calibrated diffusive isochrones reproduce well within the observational errors the position in the $M_{\rm V} - T_{\rm eff}$ plane of metal poor field subdwarfs with accurate parallaxes and empirical values of $T_{\rm eff}$ (from the IRFM method), for reasonable assumptions about their age. However, with the observational sample considered here and taking into account the existing observational uncertainties, it is impossible from this comparison to demonstrate that diffusion is fully efficient in Population II stars.

ii) MS-fitting distances obtained using current samples of Hipparcos subdwarfs and standard isochrones are negligibly affected by atomic diffusion.

iii) The estimated subdwarfs ages and age dispersion are strongly modified when diffusion is properly considered for the subdwarfs isochrones (absolute ages are significantly reduced). Since the actual metallicity of subdwarfs in the TO region can be very different from the initial one, one must take into account this effect when deriving age-metallicity relations.

iv) The value of $\Delta Y/\Delta Z$ in the Galactic Halo metallicity range turns out to be systematically underestimated (by $\delta(\Delta Y/\Delta Z)\approx$1-2) if standard isochrones are employed.

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