PRIMORDIAL HELIUM AND $\Delta Y/\Delta Z$ FROM H II REGIONS AND FROM FINE STRUCTURE IN THE MAIN SEQUENCE BASED ON HIPPARCOS PARALLAXES *

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Abstract. The primordial helium abundance $Y_{\rm P}$ is important for cosmology and the ratio $\Delta Y/\Delta Z$ of the changes relative to primordial abundances constrains models of stellar evolution. While the most accurate estimates of $Y_{\rm P}$ come from emission lines in extragalactic H II regions, they involve an extrapolation to zero metallicity which itself is closely tied up with the slope $\Delta Y/\Delta Z$. Recently certain systematic effects have come to light in this exercise which make it useful to have an independent estimate of $\Delta Y/\Delta Z$ from fine structure in the main sequence of nearby stars. We derive such an estimate from Hipparcos data for stars with $Z \leq Z_\odot$ and find values between 2 and 3, which are consistent with stellar models, but still have a large uncertainty.

Key words: galaxies: abundances, ISM: abundances, stars: abundances, stars: evolution

1. Introduction

One success of Big-Bang cosmology has been to predict primordial abundances of light elements (e.g. Copi, Schramm and Turner, 1995); but precise determination of each primordial abundance involves difficulties, both from measurements and in extrapolating through evolution that has taken place in the meantime. In particular, it has been pointed out by Hata *et al.* (1995) that with some widely accepted figures for primordial abundances, specifically with D/H $\leq 3 \times 10^{-5}$ (Tytler, Fan and Burles, 1996) and $Y_{\rm P} \leq 0.242$ or 0.243 with 95% confidence (Pagel *et al.* 1992, hereinafter PSTE; Olive, Skillman and Steigman, 1997), there is actually inconsistency with the 'standard' Big-Bang nucleosynthesis theory assuming 3 massless neutrino types.

* Based on data from the ESA Hipparcos astrometry satellite

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This conflict can be resolved if there are even quite small deficiencies in the data. The primordial deuterium abundance could be higher (e.g. Songaila, Wampler and Cowie, 1997) or the primordial helium abundance could be higher, or both. Recently several results have emerged favouring the higher helium abundance: Hata *et al.* (1996) have refined the arguments from D + ^{3}He (cf. Yang *et al.*, 1984) to derive a 95% confidence bound on deuterium, D/H $\leq 6.2 \times 10^{-5}$ implying $Y_{\rm P} \geq 0.243$; allowance for ionized hydrogen associated with Lyman-α forest clouds indicates $1 \leq \eta_{10}/4 \leq 1.5$ implying $0.243 \leq Y_{\rm P} \leq 0.247$ (Weinberg *et al.*, 1997); and a new study of extragalactic H II regions by Izotov, Thuan and Lipovetsky (1997, hereinafter ITL) has given $Y_{\rm P} = 0.243 \pm 0.003$ (s.e.), which is more consistent with the above bounds on baryonic density. The origin of the difference in this latter value from that of PSTE does not lie in the use of different atomic data, nor in any significant difference in the helium abundance for objects in common with PSTE or with Skillman and Kennicutt (1993) and Skillman *et al.* (1994) who also derived values close to 0.23, but is largely the result of a lower $\Delta Y/\Delta Z$ slope resulting from their rejection of I Zw 18 which is still the least heavy-element enriched H II galaxy known. The justification for that rejection is discussed below. Anyway, ITL find a slope $\Delta Y/\Delta Z = 1.7 \pm 0.9$, in contrast to the value of about 4 found by PSTE and this translates directly into the discrepancy between the two values of $Y_{\rm P}$. Now an estimate of $\Delta Y/\Delta Z$ (although not of $Y_{\rm P}$ itself, because of degeneracy with the mixing length) can also be obtained from fine structure in the main sequence of nearby stars, and so we have attempted to make such an estimate as will be described later.

2. Problems with extragalactic H II regions

Olive, Skillman and Steigman (1997) have presented a plot showing ITL's helium data in comparison with the others and suggest that the difference arises mainly from the fact that ITL's data do not go to the lowest metallicities available, after rejection of IZw 18. However, in the meantime, Izotov *et al.* (1997) have published a new analysis of another low-metallicity H II galaxy, SBS 0335–052, which fits the regression of ITL, whereas an earlier study of the same object by Melnick, Heydari-Malayeri and Leisy (1992) had fitted that of PSTE. This gives an opportunity to look for the cause of the difference. SBS 0335 has two major components, of which one has λ 4471 strongly affected by an underlying absorption line, while the other one looks clean. Some results from the two sets of authors for the latter component are shown in Table I.

The table shows excellent agreement for the raw measurements of the atomic He$^+$/H$^+$ ratio y^+, before correcting for collisional excitation from the 2^3S level. This correction is proportional to electron density n_e, which was estimated by Melnick *et al.* from the [S II] line ratio and by Izotov *et al.* by demanding consistency between the three lines in the table and λ 7065, resulting in smaller corrections,

Table I
Helium abundances in SBS 0335–052B

	y^+ (raw)		y^+ (corr.), y^{++}	
	Melnick *et al.* 92	Izotov *et al.* 97	Melnick *et al.* 92 n_e(SII) = 220	Izotov *et al.* 97 n_e(HeI) = 150
4471	.078	.076	.073 ± 8	.072 ± 4
5876	.084	.085	.075 ± 2	.079 ± 1
6678	.082	.081	.080 ± 4	.079 ± 3
mean y^+			.075 ± 5	.078 ± 1
y^{++}			.001	.003
y			.076 ± 5	.081 ± 2
Y			.233 ± 16	.245 ± 6

Table II
Weak helium lines in IZw 18

	theor.	meas.
$\frac{4388}{4471}$	0.12	0.10 ± .03
$\frac{4922}{4471}$	0.26	0.23 ± .03

especially for λ 5876 which carries the most weight in the final average. Both methods are subject to errors, which should have been included in the error budgets. In the Izotov *et al.* results, there is a significant discrepancy between 5876 and 4471, which can be explained in one of two ways: either 4471 is affected by underlying absorption or their collisional correction is an underestimate.

As was pointed out by PSTE, the effect of underlying absorption can be estimated by measuring the intensities of weak helium emission lines that are nevertheless strong in absorption, e.g. $\lambda\lambda$ 4026, 4388 and 4922 and comparing with theoretical intensities (Brocklehurst, 1972; Smits, 1996). Such measurements are not available for SBS 0335, but some are available for IZw 18, both from PSTE and from ITL, the latter being apparently somewhat more precise. Their results are shown in Table II.

It can be seen from the table that there is indeed a 1σ deficiency in the line ratios, which provides some evidence for absorption underlying λ 4471. For example, given that 4922 and 4471 have absorption-line strengths in a ratio of about 1:1.5 (Auer and Mihalas, 1972), the 10 per cent deficiency in their emission ratio would correspond to about a 4 per cent underestimate of 4471. A good quantitative estimate would need spectra with better resolution and signal:noise than are available at present, but the correction could amount to several per cent. Since λ 5876 is unusable for IZw 18 because of absorption by Galactic sodium and λ 6678 is not guaranteed to be free from underlying absorption, it is indeed quite possible that the current estimates of helium in IZw 18 (and possibly other very low-metallicity systems) are a few per cent too low and that the ITL solution is closer to reality. In the next sections we investigate the $\Delta Y/\Delta Z$ slope on the basis of stellar data.

3. Fine structure in the main sequence

As has been discussed previously by Perrin *et al.* (1977) and Fernandes, Lebreton and Baglin (1996), the location of the stellar main sequence as a function of metallicity is affected by $\Delta Y/\Delta Z$ because concomitant changes in Y and Z push the sequence in opposite directions. This can be seen from quasi-homology relations of the form (Cox and Giuli, 1968; Fernandes, Lebreton and Baglin, 1996)

$$\frac{L}{f(T_{\rm eff})} \propto \epsilon_0^{0.32}\kappa_0^{0.35}\mu^{-1.33}, \tag{1}$$

where the energy generation constant $\epsilon_0 \propto X^2$, the opacity constant $\kappa_0 \propto (1+X)(Z+Z_0)$ with $Z_0 \simeq 0.01$ and the molecular weight $\mu \propto (3+5X-Z)^{-1}$ leading to a magnitude offset above the zero-age zero-metallicity main sequence where $X = X_0 \simeq 0.76$

$$\begin{aligned} -\Delta M_{\rm bol} \;=\; & 1.6\log\left[1-\frac{Z}{X_0}\left(1+\frac{\Delta Y}{\Delta Z}\right)\right] \\ & +0.87\left[\log\left\{1-\frac{Z}{1+X_0}\left(1+\frac{\Delta Y}{\Delta Z}\right)\right\}+\log\left(1+\frac{Z}{Z_0}\right)\right] \\ & +3.33\log\left[1-\frac{5Z}{3+5X_0}\left(1.2+\frac{\Delta Y}{\Delta Z}\right)\right]. \end{aligned} \tag{2}$$

For high metallicities, around $0.7Z_\odot \leq Z \leq 1.5Z_\odot$, the effects of Y and Z cancel out for $\Delta Y/\Delta Z \simeq 5.5$ (Fernandes *et al.*, 1996), but this is not the case for lower metallicities (e.g. Cayrel, 1968). Perrin *et al.* (1977) and Fernandes *et al.* (1996) tested stellar main sequences derived from ground-based parallaxes for relatively metal-rich stars against theoretical main sequences roughly corresponding to Eq. (2). Perrin *et al.* found no correlation with metallicity, suggesting quite a high $\Delta Y/\Delta Z$, but with a large uncertainty, whereas Fernandes *et al.*, lacking metallicity data and examining just the scatter, deduced only that $\Delta Y/\Delta Z \geq 2$. In this investigation we use Hipparcos parallaxes (ESA, 1997) to investigate a sample of mainly metal-poor stars based on a proposal submitted by one of us (BEJP) in 1982.

In the case of an old stellar population, direct application of Eq. (2) is not very useful in practice (as well as not being very accurate) because the effects of stellar evolution increase sharply with luminosity above, say, $M_V \simeq 5.5$, so that the sequences cannot be expected to run straight and parallel over a wide range of luminosities. It is more useful to translate Eq. (2) into a range of log $T_{\rm eff}$ at a fixed absolute magnitude using the slope of the evolved main sequence, which is about 20 magnitudes per dex in $T_{\rm eff}$. We thus derive

$$\begin{aligned} -\Delta \log T_{\rm eff} \;=\; & 0.08 \log\left[1 - \frac{Z}{X_0}\left(1 + \frac{\Delta Y}{\Delta Z}\right)\right] \\ & +0.0435\left[\log\left\{1 - \frac{Z}{1+X_0}\left(1 + \frac{\Delta Y}{\Delta Z}\right)\right\} + \log\left(1 + \frac{Z}{Z_0}\right)\right] \\ & +0.167 \log\left[1 - \frac{5Z}{3+5X_0}\left(1.2 + \frac{\Delta Y}{\Delta Z}\right)\right]. \end{aligned} \quad (3)$$

Since the terms in Z are small, apart from $(1+Z/Z_0)$, we can expand the logarithms, also making use of $X_0 \simeq 0.765$, to give

$$\Delta \log T_{\rm eff} \simeq 0.01Z + 0.11Z(1+\Delta Y/\Delta Z) - 0.044\log(1+Z/Z_0). \quad (4)$$

The older quasi-homology relation given by Faulkner (1967):

$$L \propto (X+0.4)^{2.67}(Z+Z_0)^{0.455} f(T_{\rm eff}) \quad (5)$$

leads to a very similar relation

$$\Delta \log T_{\rm eff} \simeq 0.124Z(1+\Delta Y/\Delta Z) - 0.057\log(1+Z/Z_0). \quad (6)$$

These relations provide a rough guide to the behaviour of numerically computed isochrones for stars fainter than $M_V \simeq 5.5$ as a function of $\Delta Y/\Delta Z$; qualitatively, the spread in the main sequences is a decreasing function of this parameter.

4. The data

From the initial sample of about 1000 stars proposed for this programme, we have selected a subsample for which the Hipparcos parallaxes have errors better than 6 per cent, and effective temperatures and metallicities are given in either or both of the catalogues by Cayrel de Strobel *et al.* (1992) and Carney *et al.* (1994). Where available, the catalogue effective temperatures ('old' $T_{\rm eff}$'s with an estimated rms error ± 100 K) have been replaced with temperatures derived using the infra-red flux method of D.E. Blackwell by Alonso *et al.* (1996); these 'new' temperatures do not seem to differ systematically from the 'old' ones, but are very much more accurate; consistency among three different infra-red colours indicates a precision close to ± 50 K. Table III gives the data for those of the subsample that are fainter than $M_V = 5.5$; effective temperatures and metallicities from Alonso *et al.* are denoted by $T^A_{\rm eff}$ and $[{\rm Fe/H}]^A$ respectively.

An important factor in comparing stellar data with theoretical isochrones is the relationship between the metallicity [Fe/H] and the heavy-element mass fraction Z. In most cases we have used the formula by Salaris, Chieffi and Straniero (1993)

$$Z = Z_0(0.638 f_\alpha + 0.362), \quad (7)$$

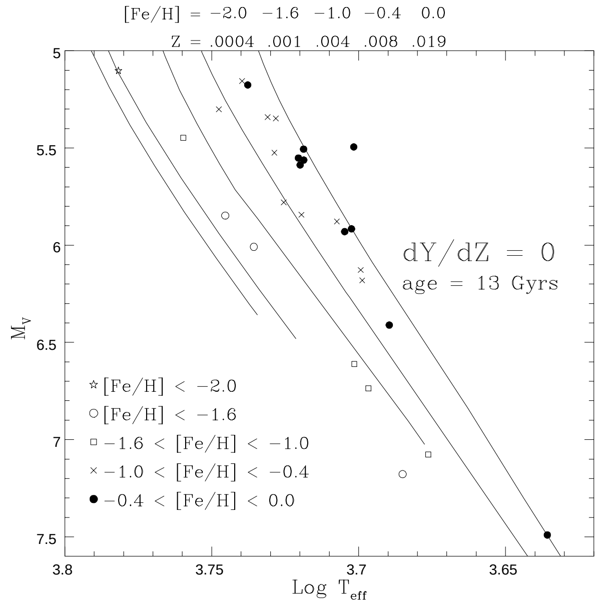

Figure 1. 13 Gyr isochrones deduced from Padova evolutionary tracks shifted by -0.009 in $\log T_{\rm eff}$ for $\Delta Y/\Delta Z$ = 0. Stellar data are plotted with 'new' effective temperatures where available. The 'star' symbol represents HD 19445. The values of Z for the 5 isochrones, together with the corresponding [Fe/H], are indicated on top of the plot.

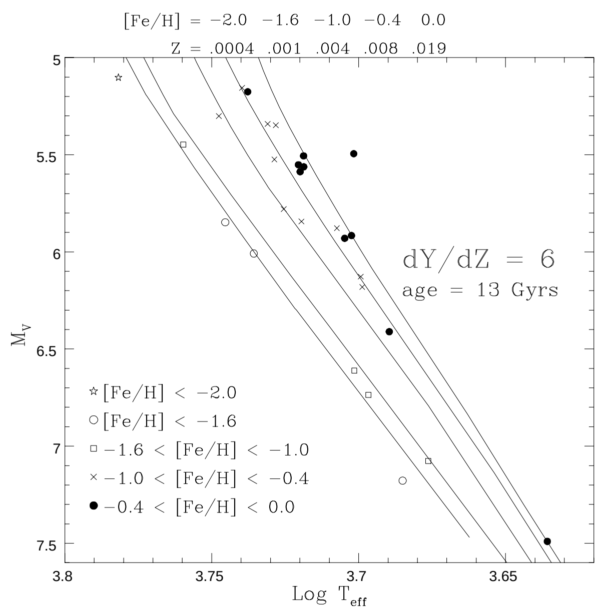

Figure 2. 13 Gyr isochrones from Padova evolutionary tracks as in Fig. 1, but for $\Delta Y/\Delta Z$ = 6. Stellar data as in Fig. 1.

Table III
The sample of lower main-sequence stars

HIC	HD	V	M_V	$\pm$	$T_{\rm eff}$	$T_{\rm eff}^A$	[Fe/H]	$[Fe/H]^A$	log Z	
5031	6348	9.15	6.18	0.10	4998		-0.67		-2.31	
5336	6582	5.17	5.78	0.03	5210	5315	-0.61	-0.67	-2.31	
10138	13445	6.12	5.93	0.01	5067		-0.24		-1.99	
18915	25329	8.51	7.17	0.04	4828	4842	-1.56	-1.64	-3.04	
19849	26965	4.43	5.91	0.01	5040	5040	-0.28	-0.17	-1.94	
23080	31501	8.19	5.59	0.08	5254		-0.33		-2.06	
38541	64090	8.31	6.05	0.07	5369	5441	-1.78	-1.82	-3.22	
39157	65583	6.99	5.87	0.03	5305	5242	-0.61	-0.60	-2.27	
57939	103095	6.44	6.63	0.02	5032	5029	-1.36	-1.35	-2.75	
58949	104988	8.16	5.59	0.07	5247		-0.23		-1.98	
62607	111515	8.15	5.55	0.07	5354		-0.81		-2.37	
73005	132142	7.77	5.88	0.03	5090	5098	-0.55	-0.55	-2.22	
74234	134440	9.45	7.08	0.11	4756	4746	-1.52	-1.57	-3.32	[a]
74235	134439	9.07	6.73	0.09	4883	4974	-1.57	-1.52	-3.32	[b]
94931	—	8.84	6.10	0.07	4859	5004	-0.87	-0.42	-2.13	[c]
98020	188510	8.83	5.85	0.10	5418	5564	-1.78	-1.80	-3.20	
99461	191408	5.32	6.41	0.01	4893		-0.32		-2.06	
104214	201091	5.20	7.49	0.03	4364	4323	-0.05	-0.05	-1.80	
106122	204814	7.93	5.56	0.05	5232		-0.28		-2.02	

[a] $[Z]$ = [Fe/H]
[b] $[Z]$ = [Fe/H]
[c] BD +41 3306

where Z_0 is the solar Z ($Z_\odot$ = 0.019) scaled according to [Fe/H] and f_α is the factor by which oxygen and α-particle elements are enhanced relative to iron, taking f_α from Pagel and Tautvaišiene (1995). Thus for [Fe/H] < -1, $Z = 2Z_0$. However, in the case of HD 134439 and 134440 we take $Z = Z_0$, following King (1997).

5. Comparison with theoretical isochrones

We have used two sets of isochrones, one computed from Padova evolutionary tracks normalized to the Sun and shifted by -0.009 in $\log T_{\rm eff}$ to fit solar-metallicity stars, the other computed by one of us (JM) normalized to low-metallicity stars and shifted by -0.01 in $\log T_{\rm eff}$ to fit the low-metallicity stars of our sample. For our purpose, anyway, it is only the spread of the isochrones that counts, not their absolute position.

In Figures 1 to 4, we compare these isochrones for the lower main sequence with the stellar data, based on 'new' effective temperatures where available. Comparison of the Padova isochrones with the data suggests that $\Delta Y/\Delta Z = 0$ is excluded,

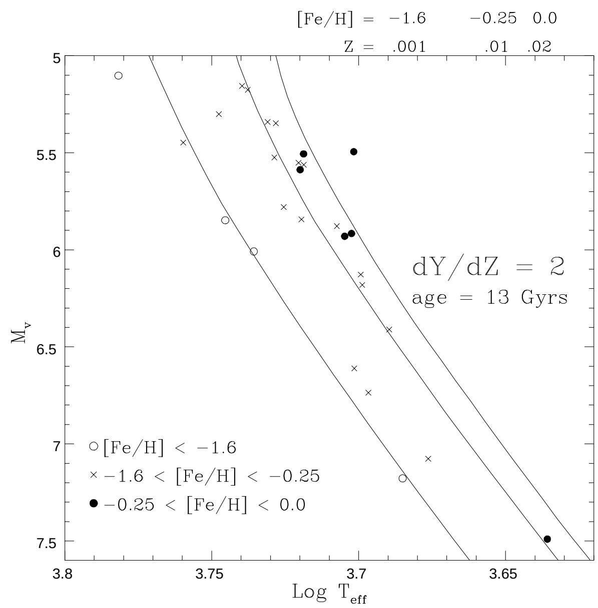

Figure 3. 13 Gyr isochrones from MacDonald evolutionary tracks and shifted by -0.01 in $\log T_{\rm eff}$ for $\Delta Y/\Delta Z$ = 2. Stellar data as in Fig. 1.

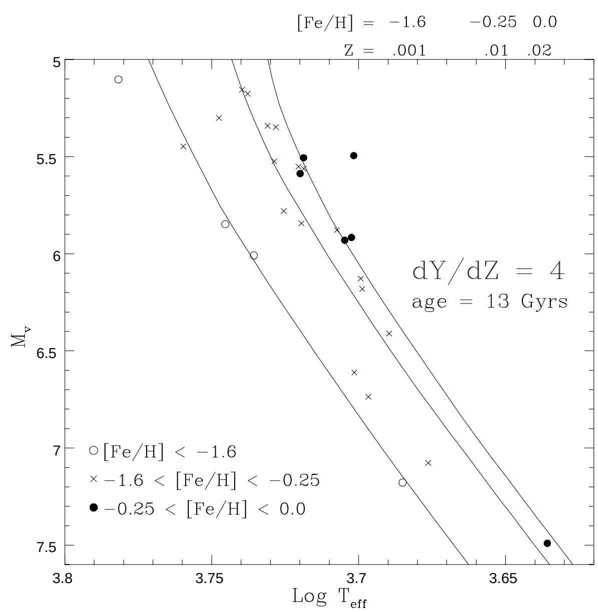

Figure 4. As Fig. 3, but for $\Delta Y/\Delta Z$ = 4,

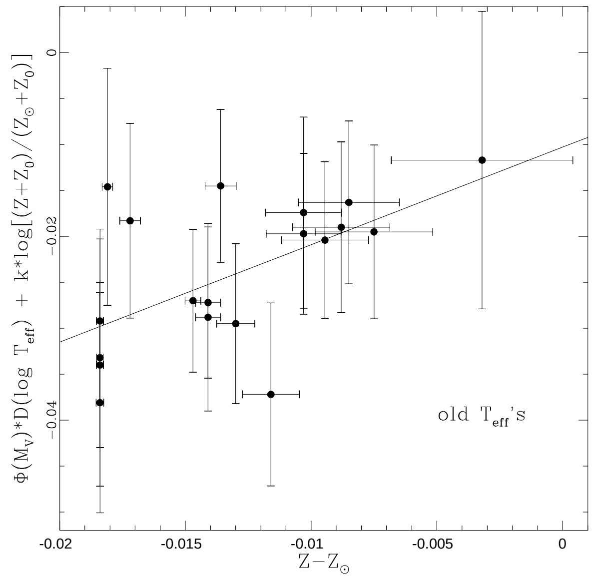

Figure 5. Maximum-likelihood regression for Padova 13 Gyr isochrones and 'old' effective temperatures for stars with $5.5 \leq M_V \leq 7.5$ assuming $\sigma_{T\mathrm{eff}} = 100$ K and $\sigma_{[\mathrm{Fe/H}]} = 0.1$. The slope corresponds to $\Delta Y/\Delta Z = 6.2 \pm 2.8$.

because the spread of the isochrones is too great, whereas $\Delta Y/\Delta Z = 6$ is too large. (With the 'old' temperatures, $\Delta Y/\Delta Z = 6$ actually gives the best fit.) The MacDonald isochrones are more widely spaced in metallicity and cover a smaller range in $\Delta Y/\Delta Z$; a value of 4 seems to give a slightly better fit than a value of 2. However, these visual impressions are largely based on the extremes in the abundance range, and the intermediate-metallicity stars are too scattered to allow any choice of $\Delta Y/\Delta Z$ from inspection. In the next section we shall try to improve on these qualitative impressions by applying a maximum-likelihood calculation based on an extension of the idea of quasi-homology.

6. Statistical analysis using quasi-homology relations

In order to be able to apply maximum-likelihood linear regression techniques to the data, we have carried out numerical experiments using *Mathematica* to find quasi-homology relations analogous to Eq. (6) applicable to the theoretical 13 Gyr isochrones in a limited range of absolute magnitude, specifically $5.5 \leq M_V \leq 7.5$, of the form

$$\phi(M_V)\Delta \log T_{\mathrm{eff}} + k \log(1 + Z/Z_0) = aZ(1 + \Delta Y/\Delta Z), \tag{8}$$

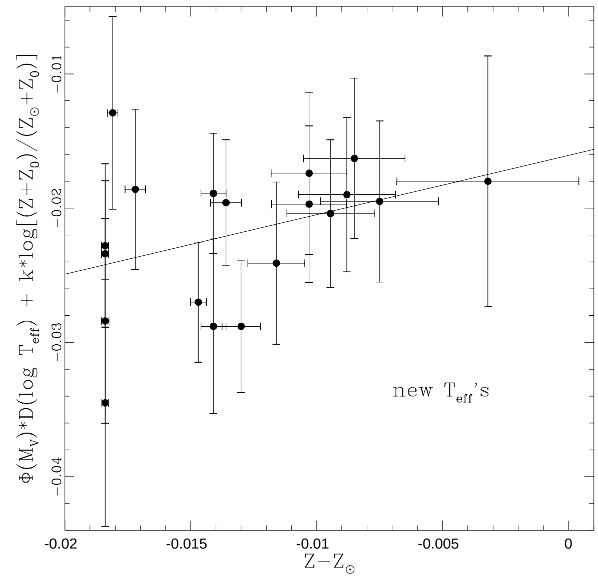

Figure 6. Maximum-likelihood regression for Padova 13 Gyr isochrones and 'new' effective temperatures for stars with $5.5 \leq M_V \leq 7.5$ assuming $\sigma_{T_{\rm eff}}$ = 50 K and $\sigma_{\rm [Fe/H]}$ = 0.1. The slope corresponds to $\Delta Y/\Delta Z$ = 2.0 ± 1.7.

where $\phi(M_V)$ is a normalization to allow for the convergence of the Padova isochrones towards low luminosities. The specific relations that we found are

$$\begin{aligned} \frac{\Delta \log T_{\rm eff}}{1 - 0.234(M_V - 6.0)} + 0.054 \log(1 + Z/Z_0) &= 0.147Z(1 + \Delta Y/\Delta Z) \\ Z_0 &= 0.0015 \end{aligned} \tag{9}$$

for Padova isochrones, and

$$\begin{aligned} \Delta \log T_{\rm eff} + 0.059 \log(1 + Z/Z_0) &= 0.128Z(1 + \Delta Y/\Delta Z) \\ Z_0 &= 0.0025 \end{aligned} \tag{10}$$

for MacDonald isochrones. The coefficients are quite similar to those in Eq. (6), but Z_0 turns out to be much lower than the widely quoted value of 0.01.

Figs. 5 and 6 show plots of the left-hand side of Eq. (9), normalized to solar metallicity, against Z for the 'old' and 'new' effective temperatures respectively, with the maximum-likelihood fit computed using a version of the program of Pagel and Kazlauskas (1992). From the figures it appears that the 'old' temperatures give a poorly defined regression with a large slope (i.e. large $\Delta Y/\Delta Z$), while the new ones give a more tidy regression with a smaller slope, but still a large error (see Table IV). The values of $\Delta Y/\Delta Z$ derived respectively from the 'old' and 'new'

Table IV
$\Delta Y/\Delta Z$ from regression analysis with 'new' temperatures

	Padova isochrones	MacDonald isochrones (α = 1.0)
$5.5 \leq M_V \leq 6.5$	3.1 ± 2.2	0.2 ± 2.5
$5.5 \leq M_V \leq 7.1$	3.3 ± 2.0	1.7 ± 2.1
$5.5 \leq M_V \leq 7.5$	2.0 ± 1.7	2.6 ± 1.8

temperatures are consistent within their combined errors, but we consider the one from the 'new' temperatures to be much more reliable.

7. Discussion

Table IV gives some solutions derived from different ranges of absolute magnitude. The MacDonald isochrones give a trend with absolute magnitude which is absent in the case of the Padova isochrones and all the results are consistent with $\Delta Y/\Delta Z$ between 2 and 3, but with a disappointingly large error. To reduce the error one needs a more complete sample of stars with known metallicities, effective temperatures and parallaxes, which will become available once the complete Hipparcos catalogue is published.

On the face of it, our stellar value of $\Delta Y/\Delta Z$ is intermediate between those claimed by ITL and by PSTE for extragalactic H II regions with similar metallicities, assuming that in this respect the two kinds of objects have undergone similar chemical evolution. Our results tend to support that assumption and to remove the higher estimates by PSTE which have inspired chemical evolution models of dwarf galaxies involving strong effects of metal-enhanced galactic winds (e.g. Pilyugin, 1993). Our results also suggest that the primordial helium abundance has been somewhat underestimated by Olive, Skillman and Steigman (1997) using data from PSTE and other preceding investigations, probably because of underlying absorption lines in some of the lowest-abundance objects, and that ITL's result $Y_{\rm P} \simeq 0.24$ is currently the best estimate available.

Chieffi, Straniero and Salaris (1995) have suggested that the mixing-length parameter α might vary systematically with metallicity. If so, this could introduce systematic errors in the estimation of $\Delta Y/\Delta Z$ from shifts in the main sequence. However, such an effect was suspected from small deviations in the main-sequence slope which are not apparent in our data, at least when compared to Padova isochrones. Values of $\Delta Y/\Delta Z$ expected from stellar models are in the neighbourhood of 2 (van den Hoek, 1997), not inconsistent with our result.

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