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Indicators of star formation: 4000 Å break and Balmer lines

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Abstract. The behaviour of the 4000 Å break index and of the equivalent width of the main Balmer lines is investigated a) for a single star as a function of effective temperature, gravity and metallicity and b) for a single stellar population as a function of age and metallicity. Consequences for the interpretation of integrated spectra are presented.

Key words: galaxies: stellar content – stars: general – galaxies: star clusters – galaxies: evolution

1. Introduction

In order to study the stellar populations of galaxies it is useful to test the capability of some spectral features of revealing the presence of stars of different ages.

The quantities here considered are the break at 4000 Å D_{4000} and the equivalent widths (EW) of the Balmer lines, in particular Hδ. Unlike several other spectral indices, they do not require high quality spectra and are therefore suitable for studying galaxies at intermediate and high redshifts.

D_{4000} is largely used to determine the star formation characteristics of distant field and cluster galaxies. Hereafter the 4000 Å break is defined as the ratio between the average flux density in ergs $\mathrm{s}^{-1}\mathrm{cm}^{-2}\mathrm{Hz}^{-1}$ between 4050 and 4250 Å and that between 3750 and 3950 Å (Bruzual 1983).

The analysis of the Balmer lines has been employed in a countless number of studies of stellar clusters, local and distant galaxies; indices including Balmer lines are useful for estimating the ages of star clusters, in the comparison between globular clusters and ellipticals and in the detection of recent starbursts in galaxies. A strong absorption Hδ line has been detected in several cluster galaxies with a wide range of colours at $0 \leq z < 0.6$ (Couch & Sharples 1987, Dressler & Gunn 1992, Caldwell et al. 1993, Belloni et al. 1995). This feature is usually interpreted as evidence of a burst of star formation ended 0.5-1.5 Gyr prior to the moment of observation (Dressler & Gunn 1983), assuming implicitely that the A-type stars responsible for the Balmer lines are *in the main sequence phase.* Here we investigate if stars in other evolutionary phases could give rise to a strong Hδ line in order to determine if and when this feature is an unambiguous sign of recent star formation.

Although largely used, these features lack a systematic analysis (such a study exists for the Hβ indices, see Buzzoni et al. 1994 and references therein), needed to clarify their dependence on metallicity (compare for instance Dressler & Shectman (1987), Kimble et al. (1989) for the D_{4000} index and Bica & Alloin (1986), Gregg (1994) for the Balmer lines). This problem is related to the well known age-metallicity degeneracy, investigated by many authors especially for old stellar populations (Jones & Worthey 1995 and references therein). Compared to previous analysis, the spectral quantities here considered are influenced also by more recent and even present star formation.

Considering stellar models instead of observed stellar libraries allows one to investigate the whole range of stellar parameters. Single stellar population (SSP) and galaxy integrated spectra are computed by means of an evolutionary synthesis model that includes both the stellar contribution and the emission of the ionized gas (Barbaro & Poggianti 1997). The advantages in taking into account a wide range of metallicities and the main advanced stellar stages, in particular the horizontal branch (HB) phase, will emerge clear from the subsequent discussion. The problem of the "second parameter", i.e. the fact that stellar clusters of comparable metallicities may have distinct horizontal branch morphologies, is not taken into account, being this question not directly relevant to the present study (see de Freitas Pacheco & Barbuy 1995 for an analysis of the Hβ indices of clusters of different HB morphologies). The total (stellar absorption + gaseous emission) EWs of the Balmer lines were measured by direct numerical integration, using the SPLOT program in IRAF and setting interactively the continuum levels and the integration limits. For SSPs and galaxies a Salpeter (1955) Initial Mass Function (IMF) between 0.1 and 100 $M_{\odot}$ was assumed.

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Table 1. D_{4000} of the elliptical model as a function of the average metallicity

Z	D_{4000}
0.03	2.26
0.02	2.21
0.01	2.07
0.008	2.03
0.005	1.94
0.003	1.85

2. D_{4000}

The variation of D_{4000} with stellar spectral type and luminosity class has been investigated by Hamilton (1985). We have compared his results with Kurucz's (1979) models of solar metallicity using the spectral type-effective temperature and luminosity class-surface gravity relations derived by Schmidt-Kaler (Landolt-Börnstein 1982, Tables 4.1.4.3 and 4.1.5.23). The comparison shows that the theoretical values fit nicely the observed ones. Using a later version of Kurucz's models does not alter the results here presented.

The behaviour of D_{4000} as a function of the stellar parameters (Fig. 1) has been derived from Kurucz's models. For stars with $3500 < T_{\rm eff} < 5500$ K (not included in Fig. 1) D_{4000} has been computed from the stellar spectra of Straizys & Sviderskiene (1972) and keeps always values above 2, reaching a maximum of 3 at $T_{\rm eff} \simeq 4000$ K.

The D_{4000} values for SSPs, computed using Kurucz's spectra, are shown in Fig. 2; the typical uncertainty is 0.1. While this index raises to high values for old solar metallicity SSPs, its value remains much lower in the case of low metallicity SSPs even after 15 Gyr.

The results obtained from the integrated spectra of elliptical models with different average metallicities are shown in Table 1, while those of other Hubble types are given in Table 2. It must be stressed that the results presented in the tables include *both* metallicity and age effects: in computing the integrated spectrum, stellar populations of different metallicities are taken into account, according to a standard chemical evolutionary model that uses the instantaneous recycling approximation. A full description of the adopted galactic models is given in Barbaro & Poggianti (1997).

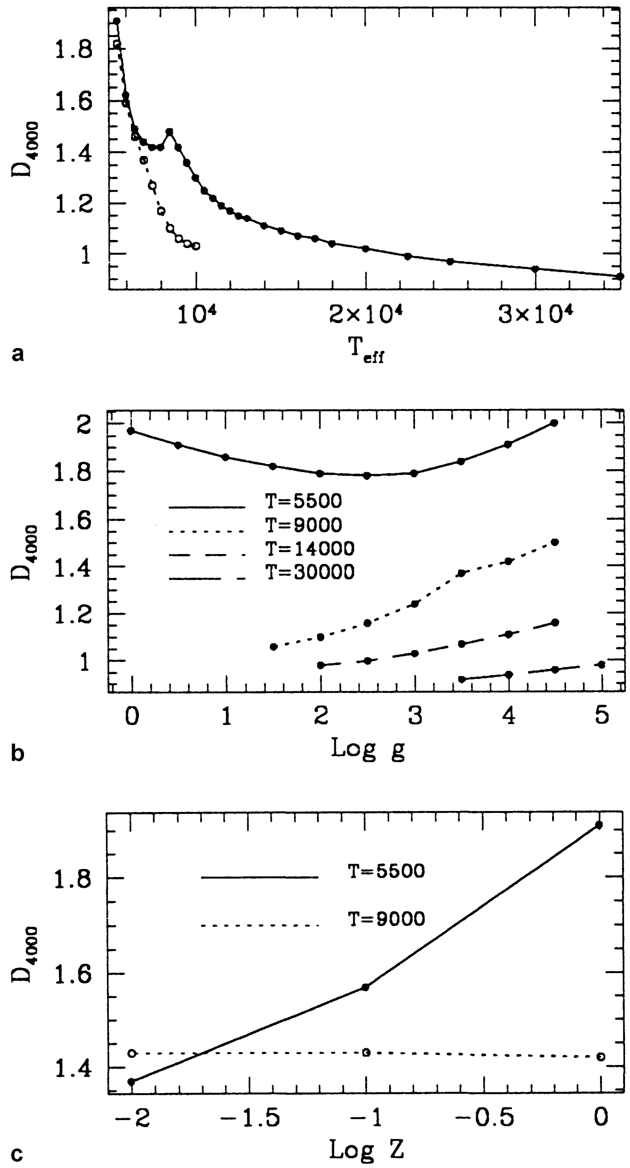

Fig. 1. D_{4000} indices of Kurucz's stellar models: a) as a function of the stellar effective temperature for solar metallicity and two different gravities (filled circles and solid line Log g=4; empty circles and dotted line Log g=1.5); b) as a function of the gravity for solar metallicity stars and 4 different effective temperatures; c) as a function of the metallicity for Log g =4 stars and two different effective temperatures

3. Hδ and other Balmer lines

Fig. 3 illustrates the behaviour of EW(Hδ) as a function of the stellar parameters; values are taken from Table 8 by Kurucz (1979). The Hδ line is strong in a range of temperatures (Fig. 3a), corresponding approximately to a lifetime interval of 0.2-2 Gyr on the main sequence. Moreover Fig. 3 shows that high EWs are reached in that range of temperatures only for high surface gravities (Fig. 3b). The maximum Hδ is therefore reached for an A0V-type star. The Hα, Hβ and Hγ lines show the same behaviour of Hδ, the only difference being a decrease of the maximum EW at lower order lines; all the following conclusions are therefore valid also for the other Balmer lines.

In order to verify if only main sequence stars have the range of temperatures and the high gravities necessary to originate strong Balmer lines, old isochrones (14 Gyr) of different metallicities are shown in Fig. 4 on a modified HR diagram (log g versus $T_{\rm eff}$). These diagrams reproduce only the isochrones and do not give the density distribution along them according to the IMF. The main evolutionary phases are easily recognized (main sequence, giant branch, HB, AGB and Post-AGB). The hottest

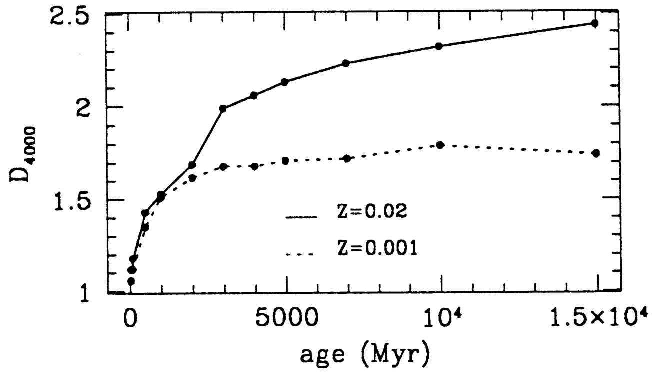

Fig. 2. D_{4000} values of single stellar populations

Table 2. Results for D_{4000} and EW(Hδ) including the gaseous emission (total) and only for the stellar component (only abs.)

Type	D_{4000}	EW(Hδ)	EW(Hδ)
		total	only abs.
E	2.21	0.9	0.9
Sa	1.91	1.1	1.2
Sb	1.75	1.0	2.0
Sc	1.54	1.4	3.2
Sd	1.42	1.7	3.7
Ex	1.31	1.2	4.1

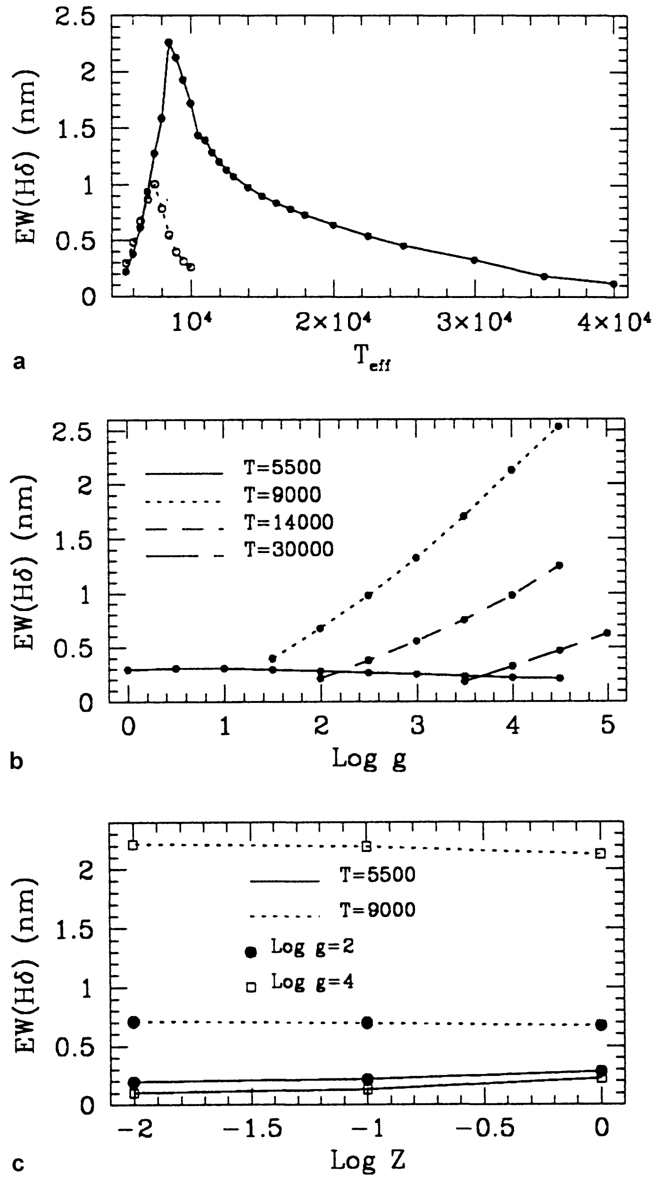

Fig. 3. EW(Hδ) of single stars: a) as a function of $T_{\rm eff}$ for solar metallicity and two different gravities (filled circles and solid line Log g=4; empty circles and dotted line Log g=1.5); b) as a function of the gravity for solar metallicity and 4 different effective temperatures; c) as a function of the metallicity for 2 different gravities and 2 different effective temperatures

Post-AGB stars lie out of the diagram on the left-bottom side (high $T_{\rm eff}$ and g) and therefore cannot contribute significantly to the Hδ line. The only stars able to reach the Hδ-strong region of Fig. 4 are the bluest horizontal branch stars with low Z. Stars with solar metallicity do not reach high enough temperatures in this phase. On the contrary, for an age 800 Myr the stellar objects in the rectangles are those around the main sequence turn-off ($1.5 - 2 M_{\odot}$), regardless of Z.

In extremely metal-rich populations, other types of stars are expected to have the required temperatures and gravities: Hot and Very Hot HB objects and AGB-manquè stars (Greggio & Renzini 1990, Liebert et al. 1994, Whitney et al. 1994, Bressan et al. 1994). Their contribution to the integrated spectra of stellar systems needs to be verified. On the other hand, if metal-rich HB stars would be responsible for the observed strong Balmer lines in some galaxies, these should belong to a restricted class of objects (the most metal-rich and most luminous) and this luminosity selection is not observed.

The EW(Hδ) of Z = $Z_{\odot}$ SSPs of different ages are shown in Fig. 5; they are computed using the Jacoby et al. stellar library (1984), whose higher spectral resolution (4 Å) compared to Kurucz's models (20 Å) allows one to study spectral features such as the Balmer lines. The typical uncertainty on the measure of EW is 0.2 Å. If the gaseous emission is not considered, EW(Hδ) reaches values > 3 Å already at 3 Myr and remains strong for about 1.5 Gyr; the maximum is reached at about 300 Myr. Comparing our results with the Balmer lines observed in globular clusters (Bica & Alloin 1986, Cohen et al. 1984), a very good agreement is found. In older SSPs (5-15 Gyr), EW(Hδ) $= 0.5 \pm 0.1$ Å. If the gaseous contribution is included, the line is in emission during the first 10 Myr (having a value of about 40 Å during the first 3 Myr), while the values at the following times remain unchanged.

The stars of the spectral library employed have $Z \sim Z_{\odot}$, therefore in principle the metallicity dependence of the results could not be investigated. We have seen however (Fig. 3c) that, given the effective temperature and surface gravity, the EW(Hδ)

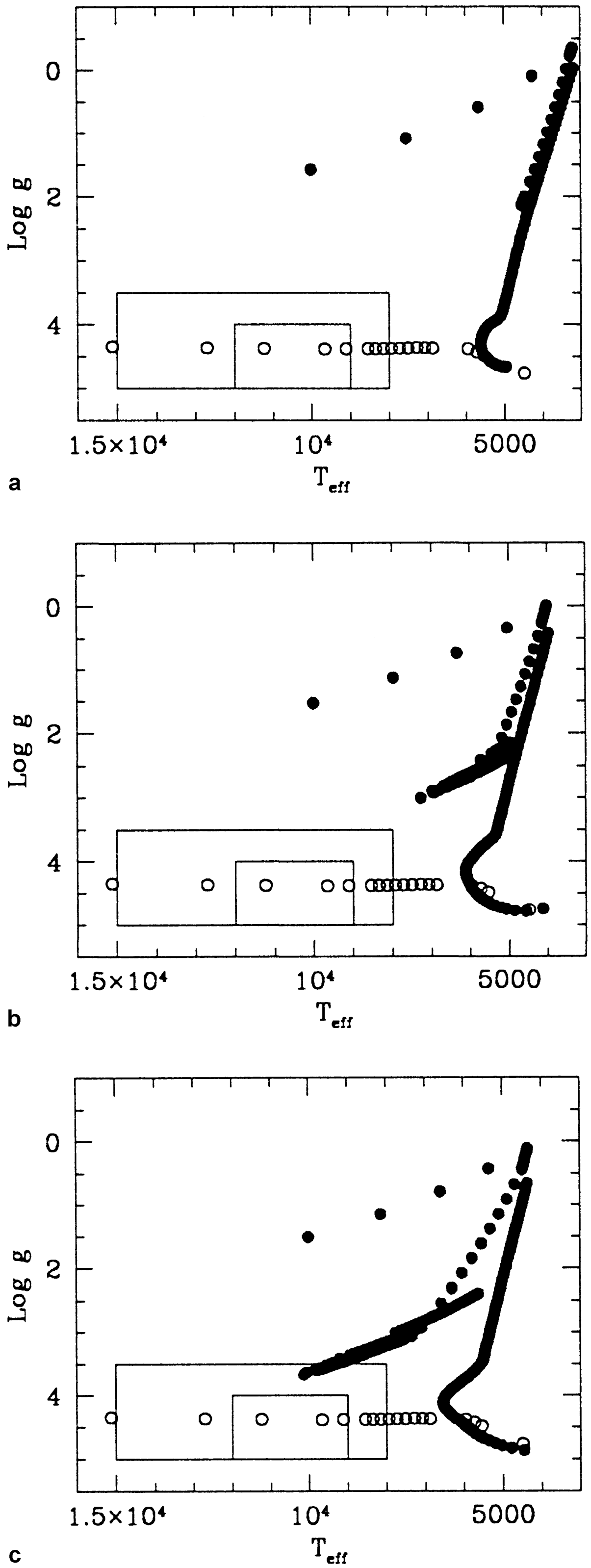

Fig. 4. 14 Gyr old isochrones of Z=0.02 (top), Z=0.001 (center) and Z=0.0001 (bottom). Rectangles show the region of highest EW(Hδ); the highest values are reached in the inner rectangle. The zero age $Z = Z_{\odot}$ main sequence is also shown (empty circles)

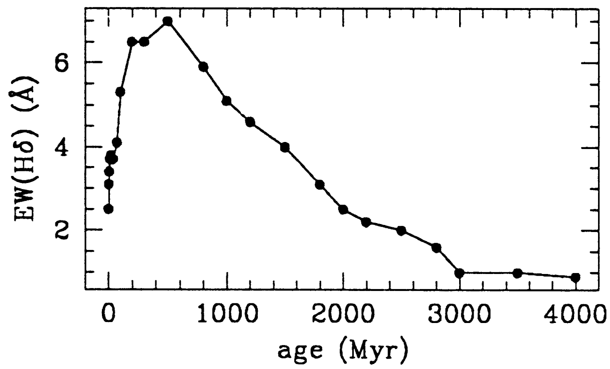

Fig. 5. EW(Hδ) of single stellar populations of solar metallicity as a function of the age of the SSP; in this case the gaseous emission is not taken into account

does not depend on the metallicity of the atmosphere. The internal structure, and consequently the position of the stars of an SSP on the HR diagram, are instead strongly dependent on the metal content. Therefore the strong Balmer lines observed in the integrated spectra of globular clusters can be studied also using the stellar library of Jacoby et al., by considering isochrones of different metallicities and adopting the Jacoby et al. spectra for any isochrone metal content. The main difference with respect to the solar metallicity case is that the EW(Hδ) at low Z (0.0001) is not negligible also for old populations, due to the presence of hot HB stars previously discussed. The dependence of the EW of two Balmer lines on the metallicity for an old SSP (14 Gyr) is shown in Fig. 6. For the Hδ line two distinct regimes are clearly visible and the relations are linear with a correlation coefficient greater than 98%:

$$\mathrm{EW(H\delta)(Å)} = -1115.8 \cdot \mathrm{Z} + 3.1 \quad \text{if } 0.0001 \leq \mathrm{Z} \leq 0.001 \qquad (1)$$

$$\mathrm{EW(H\delta)(Å)} = -21.0 \cdot \mathrm{Z} + 2.0 \quad \text{if } 0.003 \leq \mathrm{Z} \leq 0.03 \qquad (2)$$

The strong gradient at low metallicities and the shallower at $Z > 0.003$ are the direct consequence of the non-monotonic behaviour of HB stars with metallicity illustrated in Fig. 4. This can account for the large spread in EW(Hδ) observed by Bica & Alloin (1986) for old globular clusters.

In the case of the $H\beta$ line (Fig. 6c,d), after the steep gradient at low Z, the line is independent of metallicity for $Z > 0.005$. This could account for the large scatter and the lack of any correlation of the Balmer lines with metallicity above [Fe/H]=-1 reported by Gregg (1993), Faber & Worthey (1993) and Gregg (1994), for which alternative hypotheses have been proposed but seem unsatisfactory (interstellar $H\beta$ emission filling, blue stragglers in post-core-collapse clusters).

4. Conclusions

This study confirms that spectral indices or equivalent widhts of Hβ and of the other Balmer lines depend on metallicity in SSPs and galaxies and therefore cannot be used as pure age indicator. On the other side, this metallicity dependence can account for

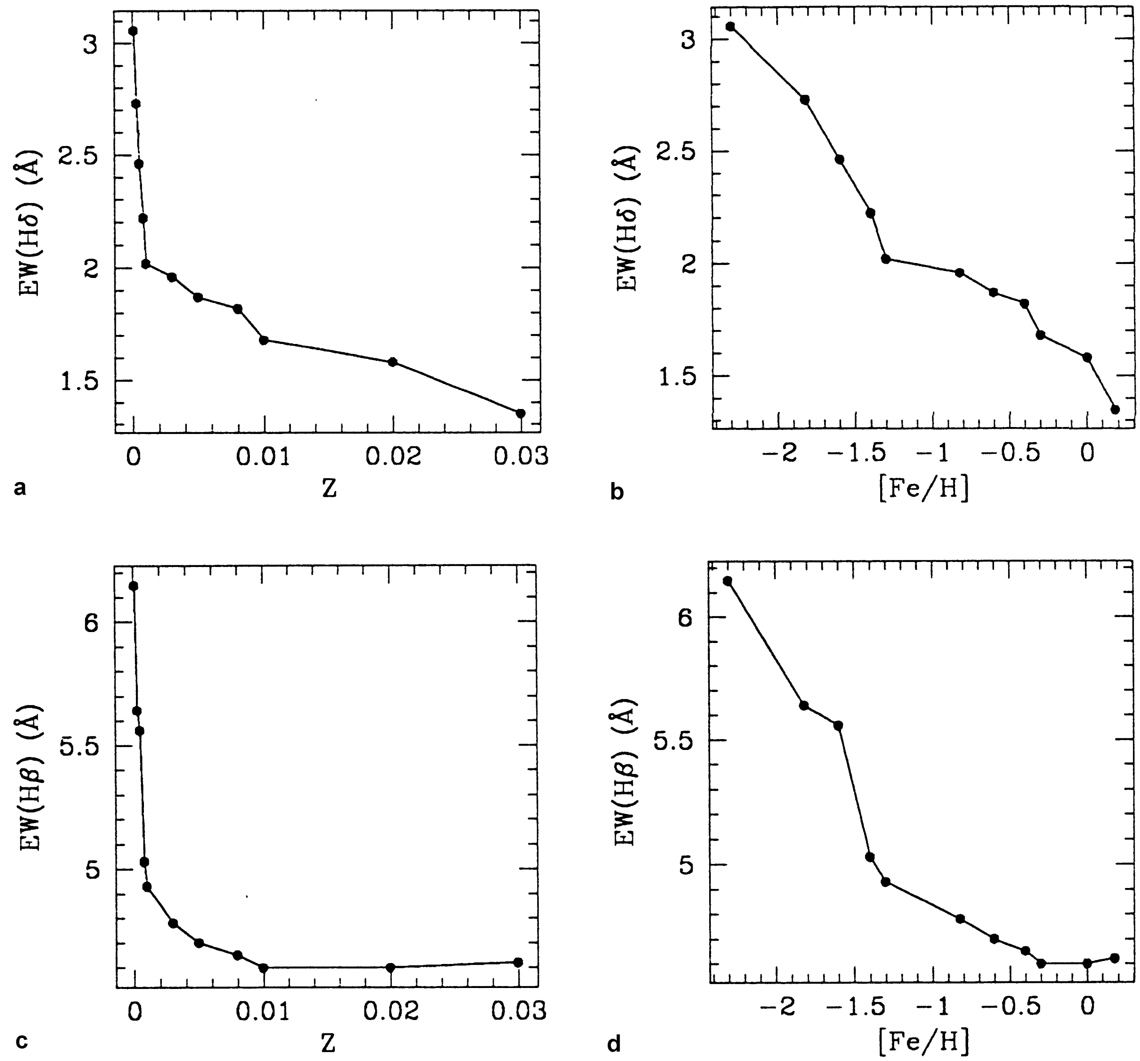

Fig. 6. EW(Hδ) and EW(Hβ) of 14 Gyr old SSPs as a function of the metallicity. [Fe/H] values are computed from Z using solar abundances ratios.

variations of the equivalent widths up to certain values (typically 1.5 Å for Hδ and Hβ for old SSPs) and above such values age differences need to be taken into account.

Results for galaxy models are shown in Table 2. In spirals the absorption line is partially filled in by the gaseous emission; the separate contributions are given as well. The very metal poor populations are unable to give rise to strong EW(Hδ) in the integrated spectrum of galaxies. This confirms that an EW(Hδ) as high as those observed in distant cluster galaxies is the signature of an enhanced star formation episode in the last 2 Gyr and cannot be due to metallicity.

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