An optimized Hβ index for disentangling stellar population ages

J. L. Cervantes* and A. Vazdekis
Instituto de Astrofísica de Canarias, La Laguna, 38200 Tenerife, Spain

Abstract

We have defined a new Hβ absorption index definition, Hβo, which has been optimized as an age indicator for old and intermediate age stellar populations. Rather than using stellar spectra, we employed for this purpose a library of stellar population spectral energy distributions of different ages and metallicities at moderately high resolution. Hβo provides us with improved abilities for lifting the age–metallicity degeneracy affecting the standard Hβ Lick index definition. The new index, which has also been optimized against photon noise and velocity dispersion, is fully characterized with wavelength shift, spectrum shape, dust extinction and [α/Fe] abundance ratio effects. Hβo requires spectra of similar qualities as those commonly used for measuring the standard Hβ Lick index definition. Aiming at illustrating the use and capabilities of Hβo as an age indicator we apply it to Milky Way globular clusters and to a well selected sample of early-type galaxies covering a wide range in mass. The results shown here are particularly useful for applying this index and understand the involved uncertainties.

Key words: globular clusters: general – galaxies: abundances – galaxies: elliptical and lenticular, cD – galaxies: stellar content

1 Introduction

To understand how galaxies form and evolve, we need to study their stellar populations as they are like fossils where the different formation and evolutionary processes are registered. Since stars are not resolved for distant stellar populations, one relies upon integrated colours and spectra to obtain their physical parameters, such as ages or metallicities. However, the integrated light of galaxies suffers the well-known age–metallicity degeneracy, making a galaxy to look redder because it is older or more metal rich (e.g. Arimoto & Yoshii 1986; Worthey 1994).

Unlike colours, spectroscopic absorption line-strength indices are more promising at breaking the age–metallicity degeneracy, but even the most popular age indicator, i.e. the Lick Hβ index (hereafter HβLICK), does show a significant dependence on metallicity, particularly for old stellar populations (Worthey 1994). Despite the fact that other age indicators based on Hγ feature have shown a larger sensitivity to age than HβLICK index, their signal-to-noise ratio (S/N) requirements are extremely high or their dependence on spectral resolution and velocity dispersion make them very difficult to apply for a large variety of data and targets (Jones & Worthey 1995; Vazdekis & Arimoto 1999).

Balmer lines are commonly used as age indicators, although they are not totally immune to metallicity effects for integrated stellar populations. In order to cope with the fact that Hβ can be filled in with nebular emission (Gonzalez 1993), indicators based on higher order Balmer lines (Hδ, Hγ) have been proposed (e.g. Worthey & Ottaviani 1997). The major drawback of these index definitions based on the Hδ and Hγ features is that they have been shown to be significantly more sensitive to the total metallicity and [α/Fe] ratio than HβLICK (Thomas, Maraston & Korn 2004; Korn, Maraston & Thomas 2005). Nowadays the development of techniques where stellar and ionized-gas contributions to the galactic spectra are simultaneously described allow us to decouple nebular emission from the absorption features (e.g. Sarzi et al. 2006). Such procedures make it possible to explore the potential of Hβ feature as an age indicator, even when gas emission is present.

Plotting Hβ index versus a metallicity indicator, measured on a set of single stellar population (SSP) spectra of different ages and metallicities, provides a diagnostic diagram that allows us to partially lift the age–metallicity degeneracy. However, it has been shown the disadvantage of using HβLICK versus various metallicity indicators for measuring mean luminosity weighted ages of early-type galaxies due to the fact that the resulting model grids are not fully orthogonal. Indeed this method leads to younger age estimates when HβLICK is plotted versus MFe, than when is plotted versus an Fe index if a galaxy is [Mg/Fe] overabundant (e.g. Yamada et al. 2006). However, a virtually orthogonal model grid is obtained when HβLICK is replaced by Hγα (Vazdekis & Arimoto 1999). Unfortunately, the very high S/N required for measuring this index (S/N (Å) > 150) limits its applicability to nearby and bright objects for which such spectra can be obtained. A more popular approach for obtaining consistent age estimates requires the use of

*E-mail: joseluis@ii.iac.es

© 2008 The Authors. Journal compilation © 2008 RAS
models that specifically take into account the non-scaled-solar elements ratios and the simultaneous measurement of several metal lines to constrain the \([\alpha/Fe]\) ratio (Thomas et al. 2004; Korn et al. 2005). However, the obtained results might depend on the details of modelling and on the particular element partition employed. Furthermore, the method is restricted to the use of the Lick Observatory Image Dissector Scanner (Lick/IDS) system of indices.

In this paper, we explore, in a systematic manner, different index definitions for the H\(\beta\) feature to find a new H\(\beta\) indicator that is virtually insensitive to metallicity, which does not require particularly high S/N. In Section 2 we describe the optimization procedure developed to find the new H\(\beta\) indicator, which makes use of a SSP library of spectral energy distributions (SEDs) at moderately high resolution. In Section 3 we introduce the new H\(\beta\) index definition and in Section 4 we tackle its main characteristics. In Section 5 we test the reliability of this index on real data. Finally, our conclusions are summarized in Section 6.

2 INDEX DEFINITION APPROACH

In the Lick system (Burstein et al. 1984; Gorgas et al. 1993; Worthey et al. 1994; Worthey & Ottaviani 1997), an index is defined in terms of a central bandpass enclosing the feature bracketed by two pseudo-continuum bandpasses at either side of the feature (blue and red). Once the average fluxes in the pseudo-continua are obtained, a line is drawn between their mid-points to represent the continuum of the central feature bandpass allowing to define an index as a pseudo-equivalent width.

The standard Lick/IDS system of indices was defined on the basis of a stellar spectral library that were not flux calibrated and had a resolution \(\sim 8.4\ \text{Å}\) full width at half-maximum [FWHM; three times lower than achieved in modern galaxy surveys, such as Sloan Digital Sky Survey (SDSS)]. Furthermore, the Lick/IDS spectral resolution is varying with \(\lambda\) (Worthey & Ottaviani 1997). The natural resolution of a galaxy spectrum is given by the convolution of the employed instrumental resolution with the velocity broadening due to galaxy dynamics. Therefore, to apply any model predictions based on the Lick/IDS system we need to smooth higher resolution spectra of galaxies with velocity dispersion values lower than that corresponding to the Lick/IDS system to match its resolution (i.e. \(\sigma \geq 200\ \text{km s}^{-1}\)). Furthermore, to apply these model predictions to higher velocity dispersion galaxies we also need to correct index measurements back to the resolution of the Lick/IDS system (an uncertain method that usually requires observing a set of reference Lick stars). Alternatively, we prefer to use here SSP SEDs at higher resolution that allow us to measure absorption line indices directly on the model spectra once smoothed to match galaxy velocity dispersion. This allows a direct comparison to the index values measured on the galaxy spectrum. This approach is advantageous for all stellar population systems, no matter its velocity dispersion nor its instrumental resolution.

We explore here the advantage of the SSP SEDs to derive new indices or to redefine previous ones, rather than employing stellar spectra or polynomial fitting functions that relate the strengths of the absorption lines to stellar atmospheric parameters. This new generation of stellar population synthesis models allows us to perform such analysis directly on the SSP spectra, allowing us to understand how sensitive to the physical parameters of the stellar populations a trial index definition is, thus avoiding the intermediate step of modelling this index for individual stars. Here we accomplish this approach by using the library of single-age, single-metallicity stellar population model spectra of Vazdekis (1999, hereafter V99) and its recent extension Vazdekis et al. (in preparation, hereafter V09) on the basis of the stellar library MILES (Sánchez-Blázquez et al. 2006). The fact that MILES is characterized by an unprecedented stellar atmospheric parameter coverage (Cenarro et al. 2007) allows predicting scaled-solar SEDs for old and intermediate ages with metallicities \(-1.7 \leq [\text{M/H}] \leq +0.2\) for the full optical spectral range (3540–7410 Å).

The use of SSP SEDs to define new indicators does not only allow us to optimize them to be sensitive to the main population parameters such as age or metallicity, but also to minimize their sensitivity, for example, to the instrumental resolution or S/N requirements. This is possible as we can simulate spectra of stellar populations for different S/N and/or resolution (or velocity dispersion) values. Furthermore, with these SSP spectra it is straightforward to simulate and analyse the effects of radial velocity (or rotation curve), spectrum shape and dust extinction on each trial index definition.

For finding a new H\(\beta\) indicator we have adopted a Lick style index definition, which consists of three bandpasses (feature and two pseudo-continua). We then change the position of these bandpasses or modify their widths until optimizing its sensitivity to a given parameter. Note that there are alternative approaches for defining indices such as those of the Rose system (Rose 1985), which are defined as the ratio between the intensity of the central peak of two spectral features. Other index definitions are for example the generic indices (Cenarro et al. 2001) or those considered pseudo-colours e.g. D4000 (Brualdi 1983).

2.1 Optimizing criteria

The goal of this work is to define a new index based on H\(\beta\) feature suitable for obtaining accurate age estimates. We have carried out a comprehensive analysis of this feature in order to obtain an index that is virtually insensitive to the total metallicity, with great stability against the smearing of this feature due to galaxy velocity dispersion (or instrumental resolution) and with as lower S/N requirement as possible. Our method to derive an optimized H\(\beta\) index definition develops a multicriteria analysis to evaluate the above requirements for each trial index definition.

2.1.1 Sensitivity to age and metallicity

Our primary criterion is obtaining an index definition for the H\(\beta\) feature that maximizes our ability to measure ages. To investigate whether metallicity effects can be decreased in the H\(\beta\) feature, we have generalized the sensitivity parameter defined in Worthey et al. (1994, see in there footnote 4):

\[
\beta/\alpha = \sqrt{\frac{\sum \left\{ \frac{(I_i/A)\left[\frac{\partial I_i}{\partial [\text{M/H}],\text{age}}\right]}{I_i}\right\}^2}{N}},
\]

where \(i\) runs for SSP models with ages older than 5 Gyr and \(-0.7 \leq [\text{M/H}] \leq +0.2\), \(i = 1, N\), and \(I_i\) is the index value measured on the \(i\) SSP model for a given index definition and \(N\) is the number of employed SSPs. Metallicity indicators should provide values above 1, whereas the value for an age indicator should tend to 0.

Among the systematically generated configuration of bandpasses, our method consists in choosing the ones that provide minimum values for the \(\beta/\alpha\) parameter. Note that the choice of bandpasses that minimizes \(\beta/\alpha\) should not depend on the stellar population synthesis models in use.
The parameter space where $\beta/\alpha$ is minimized covers the ages and metallicities for most early-type galaxies (Trager et al. 1998) and, for the H$\beta$ case, represents the parameter subspace where the age sensitivity is lower and where the metallicity has the larger effects. In other words, we are optimizing our indicator to be sensitive to the age for the worst possible cases.

2.1.2 Spectral resolution and velocity dispersion

One of the mentioned advantages of using the SSP SEDs at higher resolution is that it is straightforward to study the effects of the velocity dispersion (or resolution) on a given index definition. The models can be smoothed to different levels, allowing us to evaluate its stability to $\sigma$ variations. Note that $\sigma$ effects might be significant for some index definitions that already are optimal according to the $\beta/\alpha$ parameter, as a sufficiently small $\sigma$ variation might decrease the obtained age sensitivities. To parametrize this effect, we calculate the partial derivative of the index versus $\sigma$ for a solar metallicity SSP model of 10 Gyr at $\sigma = 150$ km s$^{-1}$:

$$
\Sigma = \frac{1}{\sigma} \left( \frac{\partial I}{\partial \sigma} \right)_{[\text{M/H}]=0.0, T=10\,\text{Gyr}, v=150\,\text{km s}^{-1}}.
$$

In a multicriteria analysis, the parameters that have been taken into account are not assigned the same weight, as our main purpose is to optimize our age resolving power. If we were to obtain an index definition that provides the largest $\sigma$ stability, we would not have retained those definitions providing the better age disentangling sensitivity. Therefore, we have discarded index definitions with $\Sigma > 4 \times 10^{-4}$ within the subset of solutions for which the $\beta/\alpha$ parameter was optimized. This is equivalent to a maximum variation of 10 per cent when comparing the index value at the nominal resolution of the models and at 250 km s$^{-1}$.

2.1.3 Signal-to-noise requirements

We have studied the S/N requirements following the analytical approach of Cardiel et al. (2003, equations 9 and 43–44). Obviously no index definition is appropriate if the required S/N is extremely high. However, achieving minimum index errors does not imply a minimum age uncertainty if the age indicator is not totally insensitive to metallicity effects. In fact, the age–metallicity degeneracy and the uncertainty of age derived from index errors are tightly correlated (Trager et al. 1998). We consider that the indicator depends solely on age, so that the uncertainty on measuring this parameter comes mostly from photon noise. Aiming at obtaining index definitions that minimize the S/N requirement, we define $\sigma[I_n]$ as the index error required to achieve a precision of 2.5 Gyr on deriving the age for a 10 Gyr and solar metallicity model. Once again we relax our S/N optimizing criterion by discarding only those definitions whose S/N (Å) requirements are above 70.

### Table 1. H$\beta$ index definitions.

| Index       | Blue pseudo-continuum (Å) | Feature (Å) | Red pseudo-continuum (Å) | $c_1$ | $c_2$ |
|-------------|---------------------------|-------------|--------------------------|-------|-------|
| H$\beta_{\text{LICK}}$ | 4827.875 4847.875 | 4847.875 4876.625 | 4876.625 4891.625 | 7.301 | 0.2539 |
| H$\beta_o$     | 4821.175 4838.404 | 4839.275 4877.097 | 4897.445 4915.845 | 9.025 | 0.2386 |

3 THE NEW H$\beta$ INDEX

According to our method for defining indices we show in this section an optimized age indicator based on the H$\beta$ feature, hereafter H$\beta_o$. Table 1 lists the limiting wavelengths of the bandpasses for the H$\beta_{\text{LICK}}$ and H$\beta_o$ indices. The bandpasses of the two indices are shown in Fig. 1. Although farther along we show plots and results obtained on the basis of V09, virtually identical results are achieved with V99 models.

H$\beta_{\text{LICK}}$ shows little sensitivity to the metallicity, as no strong metallic lines are included in the wavelength range of the index definition (Korn et al. 2005). However, this dependence is not negligible as inferred from the non-orthogonal model grids resulting when this index is plotted versus the metallicity indicator [MgFe] (Yamada et al. 2006). Furthermore, this prevents us to derive a unique age, when different metallicity indices are used if the analysed galaxies do not have scaled-solar abundance patterns, particularly for old galaxies (see, for example, their fig. 9). Metallic lines within H$\beta$ are mainly dominated by Mg via MgH absorption (Tripicco & Bell 1995), Ti (Tantalo & Chiosi 2004) and Cr at $\sim$4885 Å (Thomas et al. 2004; Korn et al. 2005).

H$\beta_o$ index definition avoids the spectral range covering those metallic lines as the red pseudo-continuum is shifted toward the red, whereas the blue pseudo-continuum is narrower to decrease the metallicity dependency. However, other metallicity variations affect the H$\beta_{\text{LICK}}$ central bandpass via a Ti line at 4871 Å and the H$\beta$ line at $\sim$4862 Å. Note that the depth of both lines show an opposed behaviour against metallicity: the higher the metallicity, the larger is the strength of the Ti line and the smaller the H$\beta$ line. These opposed responses at increasing metallicity are not balanced by each other within H$\beta_{\text{LICK}}$ index definition. This index compensates this effect in part by incorporating a metallicity dependence on the red pseudo-continuum. In fact, it overcompensates the global effect leading to a higher metallicity sensitivity. H$\beta_o$ extends to the blue the blue-wing of the central bandpass to introduce the required metallicity dependence, thus avoiding to introduce Cr in the red pseudo-continuum, which causes the variation of H$\beta_{\text{LICK}}$ with metallicity (Fig. 1).

Fig. 2 shows H$\beta_{\text{LICK}}$ and H$\beta_o$ index values as a function of the age of the SSP for different metallicities, at the nominal resolution of the models (left) and at 225 km s$^{-1}$ (right). The plot shows how H$\beta_o$ is significantly less sensitive to the metallicity than H$\beta_{\text{LICK}}$ as the lines representing models of different metallicities lay almost on the same curve, particularly for the higher metallicities (i.e. [M/H] $\geq$ $-$0.7). Note that this also applies for SSPs with ages below 5 Gyr.

3.1 Age–metallicity degeneracy

We obtain for H$\beta_o(\beta/\alpha) < 0.01$. For comparison, the standard H$\beta_{\text{LICK}}$ index provides $\beta/\alpha \simeq 0.45$ (see Table 2), confirming

---

1 Coefficients $c_1$ and $c_2$, listed in Table 1, are calculated from their equations (43) and (44) according to the index definitions provided in that table.

2 This broadening is similar to the Lick/IDS resolution at $\sim$5000 Å.
that the new index definition increases significantly the age sensitivity.

3.2 Spectral resolution and velocity dispersion

Hβ_{LICK} presents a lower $\Sigma$ value than Hβ_o (Table 2, $\approx 0.1$ against 0.19 for Hβ_o).

Fig. 3 shows that both Hβ_{LICK} and Hβ_o depend very little on resolution. In fact this dependence is lower than 5 per cent when comparing the index value at 300 km s$^{-1}$ and at the nominal resolution of the models. Despite the fact of the slightly larger dependence of Hβ_o index on $\sigma$, this dependence does not affect its age sensitivity since $\beta/\alpha$ is always lower than 0.15, and much lower than the value obtained for Hβ_{LICK} (see Fig. 4).

3.3 Signal-to-noise

Table 2 lists $\sigma[I_n]$ in percentage. Hβ_o requires slightly higher S/N than Hβ_{LICK} to distinguish the age once the metallicity is known.

However, would we have considered the real error on the age, its derivation would have been different due to the fact that any metallicity information had been taken into account in $\sigma[I_n]$. The real S/N requirements to derive the age with precision is tightly related to the metallicity dependence of the Hβ index definition.

To estimate the age accuracy determination for an index definition when we neglect the metallicity, we can focus for example on a 10 Gyr model, which is representative of the subspace of ages older than 5 Gyr and metallicities in the range $-0.7 \leq [M/H] \leq +0.2$, where most early-type galaxies are located (Trager et al. 1998). We then simulate the S/N effects on the spectrum and test the age accuracy using a plot such as that of Fig. 2. The obtained results are shown in Fig. 5, where the age uncertainty of Hβ_{LICK} decreases asymptotically to $\sim 5.1$ Gyr with increasing S/N, while the minimum age uncertainty associated to Hβ_o is $\sim 1$ Gyr at a S/N (Å$^{-1}$) $\sim 250$. This means that the maximum age accuracy achieved with Hβ_{LICK} is always lower than that of Hβ_o, no matter the spectrum quality, since this new index is much less sensitive to metallicity.

4 CHARACTERIZATION OF Hβ_o

In this section we fully characterize Hβ_o and discuss its major uncertainties with several aspects that might influence its ability as an age indicator.

3 This plot can be used to prepare observations for galaxies older than 5 Gyr and with metallicities higher than [M/H] = 0.7.
4.1 Sensitivity to abundance ratio variations

An index definition includes the contribution of various chemical species, despite the fact that a given element, which uses to name the index, might be its major contributor. As giant elliptical galaxies show [Mg/Fe] overabundance compared to the scaled-solar element partition we need to assess the influence of such abundance ratios on our index definition and on its ability to disentangle mean ages.

As this task is difficult to accomplish with models based on empirical stellar spectra, the use of theoretical atmospheres to compute stellar spectra for a large variety of element mixtures is an advantage (Tripicco & Bell 1995). In order to quantify the dependence of $H\beta_o$ on [$\alpha$/Fe] we should use SSP models with varying abundance ratios. We use the approach described in Cervantes et al. (2007) as it is based on the same model that we have employed here, where varying [$\alpha$/Fe] has been implemented via differential correction making use of Coelho et al. (2005) stellar library. Note that alternative SSP model SEDs computed with non-scaled-solar ratios have been recently published by Coelho et al. (2007). The Cervantes et al. (2007) model spectra cover two choices of partitions, [$\alpha$/Fe] = 0.0 and 0.4, where O, Ne, Mg, Si, S, Ca and Ti are flat enhanced, whilst all the other elements follow Fe. The relation between the total metallicity [M/H] and the iron content [Fe/H] is modified as

$$[M/H] = [Fe/H] + \alpha [\alpha/Fe]$$

![Figure 2. $H\beta_{LICK}$ and $H\beta_o$ indices measured on the V09 SSP spectral library at the nominal resolution of these models (left, FWHM = 2.3 Å) and at a resolution similar to that of the Lick/IDS system (right, FWHM ~8.4 Å).](image)

![Figure 3. Evolution of $H\beta_{LICK}$ (dashed line) and $H\beta_o$ (solid line) versus spectral resolution ($\sigma$). The line represents the mean values for SSPs older than 1 Gyr. Although $H\beta_o$ index is more dependent on $\sigma$, the variation is lower than 5 per cent at $\sigma < 250$ km s$^{-1}$.](image)
α-enhancement with respect to the scaled-solar model, and Hβα is virtually insensitive to metallicity as a function of σ out to σ ~ 300.

Figure 4. Generalized Worthey’s parameter, β/α, versus model spectral resolution (σ). This plot shows that Hβα is virtually insensitive to metallicity as a function of σ out to σ ~ 300.

At a given [M/H], the sensitivity of an index to [α/Fe] can be evaluated as

\[
\Lambda_{[\alpha/\text{Fe}]} = \left( \frac{I_{[\alpha/\text{Fe}]=0.4,[\text{Fe}/\text{H}]=-0.3} - I_{[\alpha/\text{Fe}]=0}}{I_{[\alpha/\text{Fe}]=0}} \right)_{[\text{M/H}]=0,10\text{Gyr}}, \tag{4}
\]

where \(I_{[\alpha/\text{Fe}]=0}\) is the index value for a 10 Gyr solar metallicity scaled-solar model, and \(I_{[\alpha/\text{Fe}]=0.4,[\text{Fe}/\text{H}]=-0.3}\) is the index value for a α-enhanced ([α/Fe] = 0.4) model of the same age and total metallicity but [Fe/H] = −0.3. \(\Lambda_{[\alpha/\text{Fe}]}\) should tend to zero if an index does not depend on [α/Fe]. \(\Lambda_{[\alpha/\text{Fe}]}\) can be interpreted as a mean deviation caused by the α enhancement with respect to the scaled-solar composition, which translates to an age (or metallicity) uncertainty. Table 3 lists the \(\Lambda_{[\alpha/\text{Fe}]}\) values, and the associated age uncertainty, corresponding to the various Balmer line index definitions (\(\Lambda_{\text{CO}}\)). We find a greater sensitivity of Hβα to [α/Fe] in comparison to that of HβLick. However, this effect is smaller than that found for the Worthey & Ottaviani (1997) higher order Balmer index definitions.

When \(A = 0\), we obtain the solar abundance of Grevesse & Sauval (1998), adopted for the synthetic spectra calculations of Coelho et al. (2005).

Table 3. Index sensitivity to [α/Fe] variations.

| Index           | \(\Lambda_{\text{CO}}\) | Age uncertainty at 10 Gyr (in Gyr) | \(\Lambda_{\text{MU}}\) | Age uncertainty at 10 Gyr (in Gyr) |
|-----------------|--------------------------|-----------------------------------|-------------------------|-----------------------------------|
| HβLick          | 0.011                    | <1                                | 0.079                   | 8–13                               |
| Hβα             | 0.119                    | 5–18                              | <0.01                   | 1–18                               |
| HβF            | 0.045                    | 8–12                              | 0.020                   | 9–12                               |
| HγF             | 0.75                     | 2.5–18                            | 1.1                     | 1–18                               |
| HβF             | 0.23                     | 4–18                              | 0.17                    | 3.5–18                             |
| HγF             | 1.7                      | 3.5–18                            | 0.4                     | 7–15                               |
| HγF             | 0.6                      | 3.5–18                            | 0.5                     | 3.5–18                             |

We are aware that the SSP SEDs with varying abundance ratios might depend on the atmospheres and spectral synthesis codes employed to compute the theoretical stellar spectra, which feed these models. In fact the computation of stellar spectra with varying [α/Fe] ratios requires adopting lists of all relevant atomic and molecular transitions, along with accurate oscillator strengths and damping constants. Furthermore, fitting detailed line profile would require the inclusion of non-local thermodynamic equilibrium (NLTE), sphericity, chromosphere effects, among other aspects. We therefore have extended the Cervantes et al. (2007) analysis by including the α enhanced theoretical stellar library of Munari et al. (2005) with the only purpose of assessing the uncertainties affecting our result. As for Cervantes et al. (2007), the model spectra cover two mixtures, [α/Fe] = 0.0 and 0.4, with O, Ne, Mg, Si, Ca and Ti enhanced as in the Coelho et al. (2005) stellar library.

Table 3 lists the results obtained for the \(\Lambda_{[\alpha/\text{Fe}]}\) parameter based on this alternative library. Surprisingly the two libraries provide similar values for nearly all the Balmer line indices but Hβ. Unlike with the library of Coelho et al. (2005), we obtain that Hβα is less sensitive to [α/Fe] variations than HβLick (see Table 3, \(\Lambda_{\text{MU}}\)). Interestingly, the HγF index shows very little sensitivity to [α/Fe] for the two libraries, which is not the case for the Worthey & Ottaviani (1997) indices. This result is in good agreement with Thomas, Maraston & Bender (2003) conclusion for the latter indices. Such dependence of the HβLick index on [α/Fe], when the library of Munari et al. (2005) is employed, has been quoted before by Tantalo & Chiosi (2004). This result is however in disagreement with the abundance ratio sensitivity found by Tripicco & Bell (1995) and Korn et al. (2005) for HβLick, as well as with our own calculations on the basis of the library of Coelho et al. (2005). Therefore, our conclusion on the greater sensitivity of Hβα on the abundance ratio in comparison to HβLick must be taken with caution, as it might depend in part on the modelling of the stellar atmospheres. A discussion of the feasibility of those stellar libraries is out of the scope of this paper and we refer the reader to Martins & Coelho (2007) for an extended analysis of these theoretical libraries and their use by SSP models. This possible drawback of the new index definition is minimized by the fact that the relative variation of Hβα to [α/Fe] is very similar to that of HβLick to the total metallicity. Hβα is however completely safe for scaled-solar element partitions, with the advantage that it provides almost orthogonal model grids. Finally, although not shown here, we note that this orthogonality is preserved when [α/Fe] enhanced models of different ages and metallicities are employed to build-up the grids.

4.2 Wavelength and radial velocity uncertainties

As absorption line indices provide us with information from relatively narrow passbands, errors in wavelength calibration, radial
velocity or rotation curve, lead to errors in our age/metallicity estimates. It is worth to note that an accurate wavelength calibration is typically around 5–10 per cent of the dispersion resulting from the adopted instrumental set-up employed in the observations. To account for this we obtain the largest wavelength errors or shifts allowed to achieve a minimum precision of 2.5 Gyr on age for a solar metallicity SSP model of 10 Gyr. In principle we should have discarded index definitions that are unstable for wavelengths shifts of 0.5 Å (i.e. typically corresponding to dispersion of 5 Å), according to our criterion. However, the set of pre-selected definitions that were virtually independent on metallicity did not show such sensitivity to wavelength shifts. For this reason we only characterize the new Hβo index for wavelength shifts and compare the obtained result with that for HβLICK. Table 2 lists the largest wavelength errors allowed to obtain a minimum precision of 2.5 Gyr for a solar metallicity, 10-Gyr-old SSP model for these two indices. This table also lists the age uncertainty corresponding to a wavelength shift of 1.5 Å (i.e. ~90 km s⁻¹). Fig. 6 shows how the β/α parameter changes with increasing wavelength shift. We see that wavelength shifts do not affect significantly the age resolving power of these two indices. Note that the age sensitivity of Hβo, is always larger than that of HβLICK. Interestingly, HβLICK increases its ability for disentangling ages if its bandpasses are shifted 1.7 Å bluward. The main characteristics and capabilities of this alternative HβLICK index definition are summarized in Appendix A.

4.3 The spectrum shape

We have tested the effect of the spectral response curve on the Hβ indices. We expect this effect to be more significant for Hβo in comparison to HβLICK. This is because the definition of Hβo spans a ~30 Å wider spectral range. We follow the test proposed by Vazdekis & Arimoto (1999) and show in Table 2 the largest differences, obtained for the oldest SSPs, when comparing the index measurements performed on the flux calibrated and continuum removed SSP spectra (using a spline3 of order 4) of similar age and metallicity. We conclude that the effect of the continuum shape on the index measurements is negligible for these two indices.

4.4 Dust extinction

Recently, absorption-line studies of integrated stellar populations are being extended to later type galaxies which may contain significant amounts of dust (e.g. de Lorenzo-Cáceres, Vazdekis & Aguerri 2007; Gorgas, Jablonka & Goudfrooij 2007). In the case of HβLICK, when dust extinction affects the SSP age determination, the errors on the physical parameters are of the same order as the ones measured in the index and thus would not likely be detected above the noise (MacArthur 2005). We should not expect significant differences for Hβo, though we have performed the same analysis followed by MacArthur (2005) who takes into account the two-component model of Charlot & Fall (2000) for the influence of the interstellar medium on the starlight. The two adjustable parameters of this model are τv, the total effective V-band optical depth affecting stars younger than 10⁷ yr and μ, the fraction of the total dust absorption contributed by diffuse interstellar medium dust.

The variations of Hβo as a function of τv, μ and age for a solar metallicity SSP model are shown in Fig. 7, where Δ index versus τv is plotted. In this figure Δ index is the difference between the index measured with and without dust, i.e. Δ index = index(τv) – index (τv = 0). Results are shown for model ages of 1 (light grey lines), 5 (grey lines) and 13 Gyr (black line). The two values for μ of 0.5 and 1.0 correspond to the solid and dashed lines, respectively. The black horizontal dotted line represents the measurement error required to distinguish 2.5 Gyr for a 10 Gyr solar metallicity SSP model, i.e. the accuracy we have imposed during our process of finding the new Hβo index. For a 1 Gyr scaled-solar model (light grey lines), HβLICK ~ 4.3 Å and Hβo ~ 5.5 Å, it corresponds to 1 per cent for Hβo and 0.2 per cent for HβLICK, in the two cases for an extreme dust extinction. For a 13 Gyr model (black lines), HβLICK ~ 1.8 Å and Hβo ~ 3 Å, it means 0.3 per cent for Hβo, since Δ index ~ 0.01 Å and 0.6 per cent for HβLICK.

As expected, the effect of extinction is larger in Hβo than in HβLICK, since the involved wavelength coverage is larger. However, the obtained effects are lower than the minimum index errors associated to the noise (Fig. 7), when extinction has been incorporated on top of the SSP SEDs. It is worth noting that although dust extinction was not considered as a parameter for the index definition process, it is not rejecting a posteriori the obtained index.

5 DISCUSSION

Estimating the mean luminosity-weighted age of an early-type galaxy represents a major step for constraining its star formation history. In this section we probe the Hβo as an age-dating indicator in real data. We apply this index to Milky Way globular clusters and to prototype early-type galaxies for which extremely high quality spectra are available.

5.1 Galactic stellar clusters

Globular clusters are ideal laboratories to test the SSP models as they can be considered as stellar populations formed in a single and homogeneous process. Milky Way globular clusters allow us to check the consistency of the Hβo age estimates as it is possible to obtain independent age/metallicity values from detailed colour–magnitude diagram (CMD) analyses.

See MacArthur (2005) for a full description of the method.
Figure 7. Hβ_{LICK} and Hβ_o index residuals, $\Delta$ index = index ($\tau_V$) − index ($\tau_V = 0$), as a function of the total effective V-band optical depth, $\tau_V$, for solar metallicity SSPs. The results for models of 1 Gyr (light grey lines), 5 Gyr (grey lines) and 13 Gyr (black lines) are shown. Different values of $\mu$ are represented as 0.5 (solid line) and 1.0 (dashed line). The black horizontal dotted lines represent the errors required for distinguishing 2.5 Gyr for a solar metallicity SSP model of 10 Gyr.

Figure 8. Hβ_{LICK} (left) and Hβ_o (right) versus CMD-derived metallicities for the globular cluster sample of Schiavon et al. (2005). The [Fe/H] values were taken from the compilation of Harris (1996). Fig. 8 shows the Hβ_{LICK} and Hβ_o indices measured on the Milky Way cluster sample of Schiavon et al. (2005) versus the CMD-derived metallicities. The [Fe/H] values are taken from Harris (1996) (the 2003 version of the McMaster catalog). We obtain for the Hβ_{LICK} sequence a Spearman rank coefficient value of −0.89, whereas for Hβ_o we obtain −0.70, indicating a milder anticorrelation for the latter. The slope of a linear fitting is −0.71 dex Å$^{-1}$ for Hβ_{LICK} and −0.36 dex Å$^{-1}$ for Hβ_o. Note that the fit for Hβ_o is virtually flat for [Fe/H] $>$ −1.0. Although we have shown in the previous section that Hβ_o is particularly optimized for higher metallicities ([M/H] $\geq$ −0.7), these results confirm the lower metallicity dependence of Hβ_o with respect to Hβ_{LICK} on the basis of real data, without the use of models, for all metallicities.

Fig. 9 shows Hβ_o and three age-dating indices versus the mean metallicity indicator [MgFe] for the same cluster sample. We see that the stellar clusters fall at the bottom of all these plots, indicating very old ages. In fact for many cases we obtain ages that are larger than the oldest models (i.e. older than the age of the Universe). These plots show the well known model zero-point problem affecting the spectroscopic age determinations from the Balmer line indices (e.g. Gibson et al. 1999; Vazdekis et al. 2001a; Schiavon et al. 2002). Recently, Mendel, Proctor & Forbes (2007) using a multi-index $\chi^2$ minimization technique analysed two Milky Way globular cluster samples (the Schiavon’s data used here and Puzia et al. 2002) to test the age estimates obtained with three different sets of updated models (Thomas et al. 2004; Lee & Worthey 2005 and our models). Although the ages inferred on the basis of their multi-index method are in agreement with the CMD-derived ages, their fig. 2 shows basically the same result, i.e. the observed Hβ values fall below the model grids for the three models. None the less the lower metal values is a result that is common to all the Balmer line-strength index definitions shown in Fig. 9. However, there are other works, working in the Lick/IDS system, in which this offset is not seen e.g. Thomas et al. (2003) where these models are used to fit the Puzia et al.’s data (both, the models and the data, also employed in Mendel et al. 2007). Note also that according to the $\Delta CO$ value listed in Table 3 for Hβ_o this offset is clearly minimized when employing models based on the Coelho et al. (2005) library. As this problem does not affect the relative age/metallicity sensitivities of the Hβ index definitions used here we refer the interested reader to the above papers for further details on this issue.

In the Hβ_o plot we are able to distinguish two populations of clusters for [MgFe] $>$ 1.5 Å, which can also be seen in Fig. 8. With this evidence in our hands we can identify these two cluster populations in the Hβ_{LICK} plot as well. However, the two cluster populations cannot be distinguished in the remaining two panels of Fig. 9, which include lower age-sensitivity indices. Therefore, this intriguing feature becomes more evident as the metallicity dependence of the Balmer index definition has been significantly minimized. An extensive study devoted to understand the origin of this feature is presented in Cenarro et al. (2008). In this study we compare the CMDs of these clusters and discuss among other aspects,
An optimized Hβ index for dating stellar populations

5.2 Elliptical galaxies

In this section we use the Hβ_o index to estimate the ages of a well-selected sample of elliptical galaxies. For selecting the sample we mainly followed two criteria: a wide coverage in galaxy mass and availability of spectra of very high S/N. The galaxy sample is composed of M32 (Rose et al. 2005) and six elliptical galaxies of Virgo, selected along the colour–magnitude relation of this cluster (Vazdekis et al. 2001b). The long-slit spectra for all the galaxies have S/N (Å⁻¹) above 150. In Figs 10 and 11, we show Hβ_LICK and Hβ_o as a function of various metallicity indicators: [MgFe], Fe₃, Mg₂, Ca4227 and CN₂. Galaxies with similar velocity dispersions were grouped separately: σ_group ≈ 135, 180, 225 km s⁻¹. To allow direct comparison between the galaxies having similar velocity dispersions, some small σ corrections were applied: the galaxies with σ_total = (σ²_galaxy + σ²_instr)¹/² < σ_group were convolved with the appropriate Gaussian to reach the corresponding σ_group.

It is commonly used the Hβ_LICK versus [MgFe] to determine both the age and the total metallicity, as the latter has been shown to be rather insensitive to possible non-scaled-solar element ratios which are found in massive ellipticals (Thomas et al. 2004). However, as Hβ_LICK has some sensitivity to metallicity the age estimates depend on the metallicity indicator in use, i.e. younger for a magnesium-dominated index and older for an iron-dominated index. This problem is usually alleviated through an iterative process with the aid of models that specifically take into account the non-scaled-solar ratios (e.g. Trager et al. 1998; Thomas et al. 2003; Tantalo & Chiosi 2004). This is no longer a problem if we use Hβ_o index as it can be seen in Fig. 11. This figure shows that the derived ages are consistent irrespective of the metallicity indicator in use. Table 4 lists the Hβ_LICK and Hβ_o age estimates for M32 and the Virgo galaxies as derived from Figs 10 and 11.

Our Hβ_o age estimates are consistent within the error bars with those derived by Rose et al. (2005) for M32 and Vazdekis et al. (2001b) and Yamada et al. (2006) for the Virgo sample using Hγ high S/N requirement set of indices. This sample of high quality spectra confirms Hβ_o as an advantageous age-dating indicator. A more detailed analysis of the ages and metallicities of these galaxies has already been performed by these authors.

6 CONCLUSIONS

We have defined a new spectroscopic age indicator, Hβ_o, which has been optimized for disentangling stellar cluster and galaxy ages. This index has a larger ability for lifting the age–metallicity degeneracy than the standard index Hβ_LICK. To achieve this, we have employed the evolutionary stellar population synthesis model of V99 and its recent extension V09 based on MILES stellar spectral library (Sánchez-Blázquez et al. 2006; Cenarro et al. 2007). As these models provide full spectra at moderately high resolution for stellar populations of different ages and metallicities, it is straightforward to investigate the behaviour of prospective index definitions as a function of relevant parameters by measuring the indices directly on the SSP spectra. This avoids us going through an intermediate step that requires the parametrization of each index definition as a
Table 4. Age estimates for M32 and Virgo elliptical galaxies.

| Galaxy | Age\(^a\) [MgFe] | Fe\(_{3}\) | M\(_{b}\) | Ca4227 | CN2 | Age\(^b\) [MgFe] | Fe\(_{3}\) | M\(_{b}\) | Ca4227 | CN2 | Age\(^c\) |
|--------|------------------|--------|--------|--------|-----|------------------|--------|--------|--------|-----|--------|
| M32    | 3.8\(^{-0.4}_{+0.4}\) | 3.4    | 4.5    | 3.8    | 3.6 | 3.1\(^{-0.2}_{+0.3}\) | 3.0    | 3.1    | 3.1    | 3.0 | 3.0    |
| NGC 4387 | 12.9\(^{-1.4}_{+1.8}\) | 13.4  | 11.1  | 15.5  | 13.4 | 14.5\(^{-1.9}_{+1.9}\) | 14.5  | 14.8  | 14.3  | 14.5 | 12.9\(^{+2.2}_{-1.5}\) |
| NGC 4464 | 15.3\(^{-1.8}_{+2.4}\) | >17.8 | 10.5  | >17.8 | >17.8 | >17.8 | >17.8 | >17.8 | >17.8 | >17.8 | 18.5\(^{+1.6}_{-1.5}\) |
| NGC 4478 | 5.8\(^{-1.0}_{+1.2}\) | 7.2    | 3.7    | 7.8    | 5.5 | 8.2\(^{-1.3}_{+1.3}\) | 8.7    | 7.4    | 8.7    | 8.2 | 8.6\(^{+1.3}_{-2.4}\) |
| NGC 4473 | 10.0\(^{-0.8}_{+0.4}\) | 12.3  | 6.0    | 17.2  | 4.6 | 11.1\(^{-0.5}_{+0.8}\) | 13.2  | 10.0  | 13.2  | 10.1 | 9.9\(^{+1.4}_{-1.9}\) |
| NGC 4365 | 11.1\(^{-1.1}_{+1.1}\) | 17.0  | 8.3    | >17.8 | 10.4 | 13.8\(^{-0.9}_{+1.2}\) | 17.8  | 10.6  | >17.8 | 11.8 | 20.0\(^{+1.0}_{-2.2}\) |
| NGC 4621 | 10.5\(^{-0.3}_{+0.3}\) | 16.2  | 7.0    | >17.8 | >17.8 | 8.4  | 10.6\(^{0.2}_{+0.3}\) | 14.3  | 9.5   | 14.1  | 9.8  | 10.6\(^{+1.0}_{-0.4}\) |

\(^a\)From metal index versus H\(_{\beta}\) LICK; \(^b\)from metal index versus H\(_{\beta}\) o; \(^c\)from Yamada et al. (2006).

Figure 10. [Mg/Fe], Fe\(_{3}\), M\(_{b}\), Ca4227 and CN2 versus H\(_{\beta}\) LICK. Top, middle and bottom panels are for galaxies with \(\sigma_{\text{group}}\) = 135, 180 and 300 km s\(^{-1}\), respectively. Model grids with various ages (solid lines) and metallicities (dotted lines) are overplotted; the age increases from top to bottom (5.6, 8.0, 11.2 and 17.8 Gyr), whereas the metallicity increases from left to right ([Fe/H] = −0.7, −0.4, 0.0 and +0.2).
function of the stellar atmospheric parameters to compute the integrated index, as it has been done, for example, for the Lick/IDS system of indices. The latter approach is not functional for optimizing trial index definitions as a function of age or metallicity, or other effects such as velocity dispersion.

We have shown that the stronger age disentangling power of Hβ_o is achieved by avoiding the metallic lines of the red pseudo-continuum of Hβ_LICK. The main characteristics and uncertainties affecting Hβ_LICK and Hβ_o indices have been studied in detail. We find that Hβ_o has a slightly higher velocity dispersion sensitivity than Hβ_LICK, but this effect is negligible in comparison to that from photon noise. The S/N required to measure Hβ_o is not significantly higher than that for Hβ_LICK, and much lower than that needed for applying Hγ_σ set of age indicators of Vazdekis & Arimoto (1999). The sensitivities of Hβ_o and Hβ_LICK to [α/Fe] variations are smaller than those found for the Worthey & Ottaviani (1997) higher order Balmer index definitions. Interestingly the Hγ_σ indices of Vazdekis & Arimoto (1999) and Vazdekis et al. (2001a) show negligible sensitivity to [α/Fe].

We have analysed the Milky Way globular cluster spectra of Schiaon et al. (2005) to test Hβ_o. The plots of their CMD-derived metallicities against Hβ_LICK and Hβ_o indices show how the metallicity sensitivity has been decreased significantly for the latter. The comparison of the observed values and the model grids resulting from plotting Hβ_o versus the [MgFe] metallicity indicator provide very old ages, in good agreement with the results obtained from various Balmer age indicators, when employing scaled-solar SSP models. However, the obtained ages are older than the CMD-derived
ages, confirming a model zero-point problem that might be affecting the analyses of the integrated light based on the Balmer indices (e.g. Gibson et al. 1999; Vazdekis et al. 2001a; Schiavon et al. 2002; Mendel et al. 2007).

We also probe the reliability of $H_\beta$, to obtain mean luminosity-weighted ages of early-type galaxies. For this purpose we used a sample of ellipticals covering a wide range in mass and $\alpha$ enhancement, for which spectra of extremely high quality are available (Vazdekis et al. 2001b; Rose et al. 2005). Unlike with $H_\beta^{\text{LICK}}$, the ages inferred from plotting $H_\beta$ versus various metallicity indicators and scaled-solar model grids are consistent, irrespective of the metallicity indicator in use. This also applies to the more massive galaxies with larger [Mg/Fe] values. We also find that the $H_\beta_o$ ages are in good agreement with the values obtained from the very high S/N requirement $H_\gamma_o$ set of indices of Vazdekis & Arimoto (1999) as listed in Yamada et al. (2006) on the basis of the same SSP models.

The results and plots shown here might be very useful, and could be taken as a guide, for preparing and optimizing observations for those willing to use $H_\beta_o$ and $H_\beta^{\text{LICK}}$ indices in their analyses.

ACKNOWLEDGMENTS

The authors would like to thank P. Coelho and B. Barbuy for their help for implementing their stellar library, N. Cardiel for his help for simulating error computations and M. Beasley, J. Cenarro and J. Falcón-Barroso for very useful suggestions and discussions. The authors thank the referee for relevant suggestions that improved the original version of the paper. JLC is a FPU PhD student and AV is on y Cajal Fellow of the Spanish Ministry of Education and Science. This work has been supported by the Spanish Ministry of Education and Science grants AYA2004-03059, AYA2005-04149 and AYA2007-67752-C03-01.

REFERENCES

Arimoto N., Yoshii Y., 1986, A&A, 164, 260
Bruzual A. G., 1983, ApJ, 273, 105
Burstein D., Faber S. M., Gaskell C. M., Krumm N., 1984, ApJ, 287, 586
Cardiel N., Gorgas J., Sánchez-Blázquez P., Cenarro A. J., Pedraz S., Bruzual G., Klement J., 2003, A&A, 409, 511
Cenarro A. J., Cardiel N., Gorgas J., Peletier R. F., Vazdekis A., Prada F., 2001, MNRAS, 326, 959
Cenarro A. J. et al., 2007, MNRAS, 374, 664
Cenarro A. J., Cervantes J. L., Beasley M., Marín A., Vazdekis A., 2008, ApJL, in press (arXiv:0810.3902)
Cervantes J. L., Coelho P., Barbuy B., Vazdekis A., 2007, Int. Astron. Union Symp., 241, 167
Charlot S., Fall S. M., 2000, ApJ, 539, 718
Coelho P., Barbuy B., Meléndez J., Schiavon R. P., Castilho B. V., 2005, A&A, 443, 735
Coelho P., Bruzual G., Charlot S., Weiss A., Barbuy B., Ferguson J., 2007, MNRAS, 382, 498
de Lorenzo-Cáceres A., Vazdekis A., Aguerri J. A. L., 2007, Int. Astron. Union Symp., 241, 420
Gibson B. K., Madgwick D. S., Jones L. A., Da Costa G. S., Norris J. E., 1999, AJ, 118, 1268
Gonzalez G., 1993, PhD thesis, Univ. California, Santa Cruz
Gorgas J., Faber S. M., Burstein D., Gonzalez J. J., Courteau S., Prosser C., 1993, ApJS, 86, 153
Gorgas J., Jablonka P., Goudfrooij P., 2007, A&A, 474, 1081
Grevesse N., Sauval A. J., 1998, Space Sci. Rev., 85, 161
Harris W. E., 1996, AJ, 112, 1487 (February 2003 version on line: http://coihue.rutgers.edu/andresj/gccat.html)
Jones L. A., Worthey G., 1995, ApJ, 446, L31
Korn A. J., Maraston C., Thomas D., 2005, A&A, 438, 685
Lee H.-C., Worthey G., 2005, ApJS, 160, 176
MacArthur L. A., 2005, ApJ, 623, 795
Martins L., Coelho P., 2007, MNRAS, 381, 1329
Mendel J. T., Proctor R. N., Forbes D. A., 2007, MNRAS, 379, 1618
Munari U., Sordo R., Castelli F., Zwitter T., 2005, A&A, 442, 1127
Puzia T. H., Saglia R. P., Kissler-Patig M., Maraston C., Greggio L., Renzini A., Ortolani S., 2002, A&A, 395, 45
Rose J. A., 1985, AJ, 90, 1927
Rose J. A., Arimoto N., Caldwell N., Schiavon R. P., Vazdekis A., Yamada Y., 2005, AJ, 129, 712
Sánchez-Blázquez P. et al., 2006, MNRAS, 371, 703
Sarzi M. et al., 2006, MNRAS, 366, 1151
Schiavon R. P., Faber S. M., Castilho B. V., Rose J. A., 2002, ApJ, 580, 850
Schiavon R. P., Rose J. A., Courteau S., MacArthur L. A., 2005, ApJS, 160, 163
Tantalo R., Chiosi C., 2004, MNRAS, 353, 917
Thomas D., Maraston C., Bender R., 2003, MNRAS, 339, 897
Thomas D., Maraston C., Korn A., 2004, MNRAS, 351, L19
Trager S. C., Worthey G., Faber S. M., Burstein D., Gonzalez J. J., 1998, ApJS, 116, 1
Tripiccio M. J., Bell R. A., 1995, AJ, 110, 3035
Vazdekis A., 1999, ApJ, 513, 224 (V99)
Vazdekis A., Arimoto N., 1999, ApJ, 525, 144
Vazdekis A., Salaris M., Arimoto N., Rose J. A., 2001a, ApJ, 549, 727
Vazdekis A., Kuntschner H., Davies R. L., Arimoto N., Nakamura O., Peletier R., 2001b, ApJ, 551, L127
Worthey G., 1994, ApJS, 95, 107
Worthey G., Ottaviani D. L., 1997, ApJS, 111, 377
Worthey G., Faber S. M., Gonzalez J. J., Burstein D., 1994, ApJS, 94, 687
Yamada Y., Arimoto N., Vazdekis A., Peletier R. F., 2006, ApJ, 637, 200

APPENDIX A: INCREASING THE AGE SENSITIVITY OF $H_\beta^{\text{LICK}}$

As a consequence of the characterization of the standard $H_\beta^{\text{LICK}}$ index definition as a function of wavelength shifts (see Section 4.2), we have shown how the $H_\beta^{\text{LICK}}$ index increases its ability to disentangle ages if all the bandpasses are shifted 1.7 Å blueward. In this appendix we provide the main properties of this alternative index definition and show the most important differences with respect to the standard, i.e. not shifted, $H_\beta^{\text{LICK}}$ index definition.

Table A1 lists the limiting wavelengths of the optimized version of this index definition (hereafter $H_\beta^{\text{LICK},o}$). The main characteristics are compiled in Table A2. $H_\beta^{\text{LICK},o}$ shows a slightly larger age disentangling power than $H_\beta^{\text{LICK}}$ (see Table 2). On the other hand, $H_\beta^{\text{LICK},o}$ is less stable against velocity dispersion than $H_\beta^{\text{LICK}}$ is. Note, however, that this dependence, tends to flatten for $\sigma > 150$ km s$^{-1}$ (see Fig. A1). Fig. A2 shows that the slightly larger age resolving power is maintained as function of $\sigma$.

Fig. A3 shows age/metallicity diagnostic diagrams based on $H_\beta^{\text{LICK},o}$. The plot shows similar age values to those obtained with $H_\beta^{\text{LICK}}$. 

© 2008 The Authors. Journal compilation © 2008 RAS, MNRAS 392, 691–704
Table A1. $H\beta_{\text{LICK,o}}$ index definition.

| Index       | Blue pseudo-continuum (Å) | Feature (Å) | Red pseudo-continuum (Å) | $c_1$ | $c_2$ |
|-------------|---------------------------|-------------|--------------------------|-------|-------|
| $H\beta_{\text{LICK,o}}$ | 4826.175 4846.175 | 4846.175 4874.925 | 4874.925 4889.925 | 8.590 | 0.2439 |

Table A2. Index characteristics and uncertainties.

| Parameter                                                                 | $H\beta_{\text{LICK,o}}$ |
|---------------------------------------------------------------------------|--------------------------|
| $\beta/\alpha$                                                             | 0.3                      |
| $\Sigma$ ($10^{-4}$ km s$^{-1}$)                                           | 2.9                      |
| Index variation by $\pm 10$ km s$^{-1}$ in $\sigma$ (per cent)             | 0.29                     |
| Maximum stability $\sigma$ range                                          | $\pm 100$ km s$^{-1}$    |
| Age uncertainty caused by $\Delta \lambda = 1.5$ Å                        | 5.7–18 Gyr               |
| Maximum $\Delta \lambda$ shifts ($\lambda, z$, rotation curve) compatible with a $\pm 2.5$ Gyr error (Å) | 0.85                     |
| [H$\beta$ (flux calibrated response curve) $- H\beta$ (continuum removed)]/H$\beta$ (f.c.r.c.) | '0.01                   |
| $S/N$ (Å$^{-1}$) required to distinguish 2.5 Gyr at 10 Gyr                | $\sim 50$                |
| Minimum age uncertainty for $S/N$ (Å$^{-1}$) $> 250$                       | 4.9 Gyr                  |
| Index sensitivity to $[\alpha/\text{Fe}]$ variations ($[\Lambda_{\text{CO}}, \Lambda_{\text{MU}}]$) | [0.12, 0.23] |

Figure A1. Evolution of $H\beta_{\text{LICK,o}}$ versus spectral resolution ($\sigma$). The line represents the mean values for SSPs older than 1 Gyr.

Figure A2. Generalized Worthey’s parameter, $\beta/\alpha$, versus model spectral resolution ($\sigma$). 
Figure A3. $\frac{[\text{Mg/Fe}]}{\text{H}_\beta_{\text{LICK}}}$, $\alpha$. Top, middle and bottom panels are for galaxies with $\sigma_{\text{group}} = 135$, 180 and 300 km s$^{-1}$, respectively. Model grids with various ages (dotted lines) and metallicities (solid lines) are overplotted; the age increases from top to bottom (5.6, 8.0, 11.2 and 17.8 Gyr), whereas the metallicity increases from left to right ($[\text{Fe/H}] = -0.7$, $-0.4$, 0.0 and +0.2).

This paper has been typeset from a T\(\LaTeX\)/\LaTeX\ file prepared by the author.