Stellar populations of early-type galaxies in different environments II
Ages and metallicities

P. Sánchez–Blázquez\textsuperscript{1,2}, J. Gorgas\textsuperscript{2}, N. Cardiel\textsuperscript{2,3}, and J.J. González\textsuperscript{4}

\textsuperscript{1} Laboratoire d’Astrophysique, École Polytechnique Fédérale de Lausanne (EPFL), Observatoire, 1290 Sauverny, Switzerland
\textsuperscript{2} Dpto. de Astrofísica, Fac. de Ciencias Físicas, Universidad Complutense de Madrid, E-28040 Madrid, Spain
\textsuperscript{3} Calar Alto Observatory, CAHA, Apartado 511, E-04004 Almería, Spain
\textsuperscript{4} Instituto de Astronomía, Universidad Nacional Autónoma de México, Apdo-Postal 70–264, México D.F, México

ABSTRACT

\textbf{Aims.} This is the second paper of a series devoted to study the stellar content of early-type galaxies. The goal of the series is to set constraints on the evolutionary status of these objects

\textbf{Methods.} We use a new set of models which include an improved stellar library (MILES) to derive simple stellar population (SSP)-equivalent parameters in a sample of 98 early-type galaxies. The sample contains galaxies in the field, poor groups, and galaxies in the Virgo and Coma clusters.

\textbf{Results.} We find that low-density environment galaxies span a larger range in SSP age and metallicity than their counterparts in high density environments, with a tendency for lower $\sigma$ galaxies to be younger. Early-type galaxies in low-density environments appear on average $\sim$ 1.5 Gyr younger and more metal rich than their counterparts in high density environments. The sample of low-density environment galaxies shows an age metallicity relation in which younger galaxies are found to be more metal rich, but only when metallicity is measured with a Fe-sensitive index. Conversely, there is no age-metallicity relation when the metallicity is measured with a Mg sensitive index. The mass-metallicity relation is only appreciable for the low-density environment galaxies when the metallicity is measured with a Mg-sensitive index and not when the metallicity is measured with other indicators. On the contrary, this relation exists for the high-density environment galaxies independently of the indicator used to measure the metallicity.

\textbf{Conclusions.} This suggests a dependence of the mass-metallicity relation on the environment of the galaxies. Our data favour a scenario in which galaxies in low density environments have suffered a more extended star formation history than the galaxies in the Coma cluster, which appear to host more homogenous stellar populations.

Key words. galaxies: abundances – galaxies: formation – galaxies: elliptical and lenticular – galaxies: evolution – galaxies: stellar content – galaxies: formation.

1. Introduction

The knowledge of the star formation history of early-type galaxies is a key test of our understanding of the galaxy formation processes. The classic vision of elliptical galaxies as old objects forming their stars at high redshift in a single episode has come into question by several studies of stellar population in these systems which found a high fraction of early-type galaxies with apparent young ages (e.g. González 1993; Trager et al. 1998; Trager et al. 2000b; Terlevich & Forbes 2002; Sánchez–Blázquez 2004).

The semi-analytical models of galaxy formation (Kauffmann 1996; Baugh et al. 1996; Cole et al. 1994; Somerville et al. 1999; de Lucia et al. 2006), in the framework of cold dark matter (CDM) cosmological model and in the current standard $\Lambda$CDM, predict extended star formation histories for early-type galaxies, with substantial fractions of the stellar population formed at relative low redshift, in agreement with the observed trends. The numerical simulations based on the semi-analytical models can reproduce impressively various features of large-scale structures from dwarf galaxies to giant galaxies and rich clusters of galaxies (e.g. Steinmetz & Navarro 2002; Klypin et al 2003). One of the keys to test
the hierarchical scenarios is to study the properties of galaxies situated in different environments, since the semi-analytical models predict that galaxies in dense clusters were assembled at higher redshift than galaxies in the field and poor groups.

This is the second paper of a series devoted to the study of the stellar content in nearby early-type galaxies. The final aim of the series is to constrain the formation epoch of the stellar content in different environments. The first paper of the series (Sánchez–Blázquez et al. 2006a, hereafter Paper I) analysed the relation of the central line-strength indices with the velocity dispersion for a sample of 98 galaxies drawn from different environments. It also presented some evidences of differences between the stellar content of galaxies in different environments. In particular, we found that the index–σ relations are driven by both age and metallicity in the sample of galaxies in low-density environments and in the Virgo cluster. However, an age variation with σ is not required to explain the index–σ relations for galaxies belonging to the Coma cluster. We also presented evidences supporting that the [Mg/Fe], [N/Fe], and probably [C/Fe] ratios increase with the velocity dispersion of the galaxy in both subsamples. In Paper I we studied the scatter in the index–σ relations, finding that this is not only a consequence of a dispersion in the age of the galaxies, but it is also due to variations of the [Mg/Fe] ratio. These variations are related to the mean ages of the galaxies, in the sense that younger galaxies exhibit, on average, lower [Mg/Fe] ratios. Furthermore, galaxies in the Coma cluster show, on average, higher [Mg/Fe] ratios than galaxies in lower environment. We also detected systematic differences in the values of some indices which were interpreted as differences in chemical abundances ratios between both subsamples.

In Paper I we analysed the raw line-strength indices and their relation with other parameters. In this paper, we compare these indices with the predictions of the stellar population synthesis models by Vazdekis et al. (2006). This library contains 1003 stars, carefully selected to cover the atmospheric parameter space in an homogeneous way. In particular, the library span a range of metallicities from [Fe/H] ∼ −2.7 to +1, and a wide range of effective temperatures. The inclusion of this library reduces the uncertainties in the models, especially at metallicities departing from solar.

Since the stars of the library are relatively flux calibrated, these models are able to predict, not only individual features for a population of a given age and metallicity, but the whole spectral energy distribution (SED). This allows to analyse the spectra of the galaxies at its own resolution, given by their internal velocity and instrumental broadening (see e.g., Vazdekis et al. 2001). The synthetic spectra have a spectral resolution of 2.3 Å and cover the spectral range 3500-7500 Å.

In spite of this capability, as we are using calibrations based on the Lick system, and in order to compare our results with previous studies, most of the analysis has been performed with the indices transformed into the Lick system. Therefore, in order to compare with the model predictions, we broadened the synthetic spectra to match the wavelength dependent resolution of the Lick stellar library (Worthey & Ottaviani 1997) and measured the indices in the same way as in the galactic spectra. We then added to the synthetic indices the same offsets that we applied to the galaxy indices. (see Paper I for details).

Figure 2 shows several index–index diagrams combining different pairs of indices. Over-plotted are the stellar population models of V06 for various ages and metallicities as indicated in the figure caption. Open and filled symbols represent LDEGs and HDEGs respectively. It is clear from the figure that galaxies span a fair range in their mean ages. This result has been previously found by other authors (González 1993; Trager et al. 1998; Trager et al. 2000a) and it is in contradiction to the classical vision of early-type galaxies as old and coeval systems.

To quantify the age and metallicity values, we interpolated in the grids using bivariate polynomials, as described in Cardiel et al. (2003). Although the highest metallicity modeled by V06 is [M/H] = +0.2, in order to obtain metallicity values for the maximum number of galaxies, we extrapolated the predictions up to [M/H] = +0.5. However, all the values above [M/H] = +0.2 have to be considered more uncertain. The errors in age and metallicity were calculated as the differences between the central values and the values at the end of the error bars, which give an upper limit to the real errors. Table 2 lists the ages and metallicities derived from several index–index diagrams, all of them combining Hβ with other metal-sensitive indices. The empty spaces in the table indicate that the galaxy lies outside the model grid, and therefore no measurements of age and metallicity have been made. The ages and metallicities presented here represent simple stellar population equivalent models (e.g. Worthey 1994; Buzzoni 1995; Bruzual & Charlot 2003; Thomas, Maraston & Bender 2003) Here we follow a similar approach, deriving the SSP parameters (age and metallicity) by comparing the observed line-strengths with the predicted index–index diagrams from a new set of models by V06. These models are an updated version of those described by Vazdekis et al. (2003) improved by the inclusion of a new stellar library (MILES) recently observed by Sánchez–Blázquez et al. (2006). This library contains 1003 stars, carefully selected to cover the atmospheric parameter space in an homogeneous way. In particular, the library span a range of metallicities from [Fe/H]~ −2.7 to +1, and a wide range of effective temperatures. The inclusion of this library reduces the uncertainties in the models, specially at metallicities departing from solar.

In spite of this capability, as we are using calibrations based on the Lick system, and in order to compare our results with previous studies, most of the analysis has been performed with the indices transformed into the Lick system. Therefore, in order to compare with the model predictions, we broadened the synthetic spectra to match the wavelength dependent resolution of the Lick stellar library (Worthey & Ottaviani 1997) and measured the indices in the same way as in the galactic spectra. We then added to the synthetic indices the same offsets that we applied to the galaxy indices. (see Paper I for details).

Figure 1 shows several index–index diagrams combining different pairs of indices. Over-plotted are the stellar population models of V06 for various ages and metallicities as indicated in the figure caption. Open and filled symbols represent LDEGs and HDEGs respectively. It is clear from the figure that galaxies span a fair range in their mean ages. This result has been previously found by other authors (González 1993; Trager et al. 1998; Trager et al. 2000a) and it is in contradiction to the classical vision of early-type galaxies as old and coeval systems.

To quantify the age and metallicity values, we interpolated in the grids using bivariate polynomials, as described in Cardiel et al. (2003). Although the highest metallicity modeled by V06 is [M/H] = +0.2, in order to obtain metallicity values for the maximum number of galaxies, we extrapolated the predictions up to [M/H] = +0.5. However, all the values above [M/H] = +0.2 have to be considered more uncertain. The errors in age and metallicity were calculated as the differences between the central values and the values at the end of the error bars, which give an upper limit to the real errors. Table 2 lists the ages and metallicities derived from several index–index diagrams, all of them combining Hβ with other metal-sensitive indices. The empty spaces in the table indicate that the galaxy lies outside the model grid, and therefore no measurements of age and metallicity have been made. The ages and metallicities presented here represent simple stellar population equivalent models (e.g. Worthey 1994; Buzzoni 1995; Bruzual & Charlot 2003; Thomas, Maraston & Bender 2003) Here we follow a similar approach, deriving the SSP parameters (age and metallicity) by comparing the observed line-strengths with the predicted index–index diagrams from a new set of models by V06. These models are an updated version of those described by Vazdekis et al. (2003) improved by the inclusion of a new stellar library (MILES) recently observed by Sánchez–Blázquez et al. (2006). This library contains 1003 stars, carefully selected to cover the atmospheric parameter space in an homogeneous way. In particular, the library span a range of metallicities from [Fe/H]~ −2.7 to +1, and a wide range of effective temperatures. The inclusion of this library reduces the uncertainties in the models, specially at metallicities departing from solar.

In spite of this capability, as we are using calibrations based on the Lick system, and in order to compare our results with previous studies, most of the analysis has been performed with the indices transformed into the Lick system. Therefore, in order to compare with the model predictions, we broadened the synthetic spectra to match the wavelength dependent resolution of the Lick stellar library (Worthey & Ottaviani 1997) and measured the indices in the same way as in the galactic spectra. We then added to the synthetic indices the same offsets that we applied to the galaxy indices. (see Paper I for details).

Figure 1 shows several index–index diagrams combining different pairs of indices. Over-plotted are the stellar population models of V06 for various ages and metallicities as indicated in the figure caption. Open and filled symbols represent LDEGs and HDEGs respectively. It is clear from the figure that galaxies span a fair range in their mean ages. This result has been previously found by other authors (González 1993; Trager et al. 1998; Trager et al. 2000a) and it is in contradiction to the classical vision of early-type galaxies as old and coeval systems.

2. Derivation of ages and metallicities

Previous works have used Lick/IDS line-strength indices to derive mean ages and metallicities using evolutionary synthesis models (e.g. Worthey 1994; Buzzoni 1995; Bruzual & Charlot 2003; Thomas, Maraston & Bender 2003). Here we follow a similar approach, deriving the SSP parameters (age and metallicity) by comparing the observed line-strengths with the predicted index–index diagrams from a new set of models by V06. These models are an updated version of those described by Vazdekis et al. (2003) improved by the inclusion of a new stellar library (MILES) recently observed by Sánchez–Blázquez et al. (2006). This library contains 1003 stars, carefully selected to cover the atmospheric parameter space in an homogeneous way. In particular, the library span a range of metallicities from [Fe/H]~ −2.7 to +1, and a wide range of effective temperatures. The inclusion of this library reduces the uncertainties in the models, specially at metallicities departing from solar.
parameters, and thus, if all the stars were not formed in a single event, they represent values weighted with the luminosity of the stars and do not necessarily reflect the age and the metallicity of the bulk of the stars in the galaxy. We have used $\text{H}\beta$ as the main age indicator as the other higher-order Balmer lines ($\text{H}\delta$ and $\text{H}\gamma$) are very sensitive to $\alpha$/Fe ratio changes at super-solar metallicities (Thomas, Maraston & Korn 2004).

2.1. The problem of the relative abundances

One aspect which is evident in Fig. 1 is that the ages and metallicities obtained with different indicators are not the same. In particular, the metallicities measured with indices such as CN$_2$, Mgb and C4668 are larger than the metallicities measured with Fe-sensitive indices such as Fe4383. This effect has been noted previously by several authors (e.g. Peletier 1989; Faber et al. 1999; Vazdekis et al. 2001; Thomas, Maraston & Korn 2004; among others) and is commonly attributed to an overabundance of Mg (O'Connell 1976), N (Worthey 1998) and C (Vazdekis et al. 2001) with respect to Fe$^1$ compared to the solar abundance partition. The differences in the relative chemical abundance ratios with respect to the solar values is one of the major roadblocks to derive reliable stellar population parameters. However, since different elements are produced in stars with different lifetimes, the study of the chemical composition of early-type galaxies is a powerful tool to disentangle the star formation history of these systems. Unfortunately, the computation of chemical abundances through the comparison with stellar population models is still in its infancy. Great efforts have been made to include the non-solar partition effects in the theoretical models through the building of $\alpha$-enhanced$^2$ isochrones (Salaris, Chieffi & Straniero 1993; Salasnich et al. 2000) and stellar model atmospheres with variations on the abundance of individual elements (Tripicco & Bell 1995). Some attempts

\begin{footnote}
1 Although we use the term overabundance, in fact Trager et al. (2000b) has shown that the differences are more likely due to a depression of Fe with respect to the solar values more than to an enhancement of the light elements.
\end{footnote}

\begin{footnote}
2 The so called $\alpha$-elements: O, Ne, Mg, Si, S, Ar, Ca, Ti, are particles build up with $\alpha$-particle nuclei.
\end{footnote}
have also been made to include these theoretical work into the SSP models (Trager et al. 2000b; Thomas et al. 2003). But, despite all these valuable works, we are still lacking models which include the effect of variations of chemical abundances ratios in a consistent way (with isochrones, model atmospheres and stellar libraries). The current models have an inconsistency between the atmospheres and the stellar interiors.

The potential effects of including isochrones with non-solar chemical abundance ratios is not clear. Tantalo, Chiosi & Bressan (1998) built a set of stellar isochrones with relative abundances of \([\alpha/\text{Fe}]\) different than solar and concluded that the models incorporating those were indistinguishable in the colour-magnitude diagram from the models with the same metallicity and \([\alpha/\text{Fe}] = 0\). Salaris et al. (1993) showed (only for metallicities lower than solar) that the isochrones with over-abundances of \(\alpha\) elements were identical to the ones scaled to solar ratios at the same metallicity, if the ratio between the mass fraction of elements with high- and low- ionisation potential were constant. However, more recently, Salaris & Weiss (1998) have suggested that at higher metallicities (near solar), the isochrones shift to higher temperatures and their shapes change as the ratio \(\alpha/\text{Fe}\) increases. Trager et al. (2001b) have analysed the effect of this change and have not found much difference in the predicted indices. However, Thomas & Maraston (2003) found large differences in the inferred ages using models which incorporate the isochrones with \(\alpha\)-enhancement with respect to the models which do not. So far, the effect of including isochrones with \([\text{C/Fe}]\) and \([\text{N/Fe}]\) different from solar has not been studied.

Another problem is that the empirical stellar libraries included in the population models are limited to stars in the solar neighborhood with, therefore, relative compositions between different elements resembling the solar one. The ratios between the different elements in these stars are not well known but, assuming that they follow the trends of the disk stars in the Galaxy, these abundances are not constant with metallicity, which, if not taken properly into account, can produce an apparent variation of the relative abundances with metallicity (Proctor et al. 2004).

For all these reasons, in this work we do not attempt to derive relative abundances of the different elements. However, with the aim of exploring the behaviour of the different chemical species, we measure the metallicity using several indices especially sensitive to variations of different elements.

For the rest of the analysis we make the assumption that the differences between the metallicities derived from various index–index diagrams, combining H\(\beta\) with other metallicity indicators, are due to changes in the sensitivity of these indicators to variations of different chemical abundances.

### 3. The SSP-parameters \(\sigma\) relation

Fig. 2 shows the ages and metallicities obtained in different index–index diagrams as a function of the velocity dispersion for both HDEGs (black symbols) and LDEGs (grey symbols). We have not plotted the dwarf galaxies of the sample, since it is not clear whether these galaxies are the faint extension of the giant ellipticals (see, for example Gorgas et al. 1997; Pedraz et al. 2002; Graham & Guzmán 2003). Error-weighted linear fits to each subsample are also shown in the figure. These fits were derived by initially performing an unweighted ordinary least-squares regression of \(Y\) on \(X\) and the coefficients from the first fit were then employed to derive (numerically, with a downhill method) the straight line data-fit with errors in both coordinates. Table 2 lists the slopes of the fits with their corresponding errors. The last two columns indicate the \(t\)-statistic obtained in the comparison of the slopes of HDEGs and LDEGs, and the probability that the slopes are different by chance. We analyse each panel separately:

- \([\text{M/H}]\) (CN\(_{2}\)–H\(\beta\)) versus \(\sigma\): While there is a correlation for the HDEGs between the metallicity and the velocity dispersion, this is not true for the LDEGs, which are compatible with a null relation. The most massive galaxies (\(\sigma > 300\) km s\(^{-1}\)) however, show the same behaviour in both environments, while for the rest of the galaxies, there exists a clear difference between the metallicity in the two galaxy subsamples.

- \([\text{M/H}]\) (Fe\(_{4383}\)–H\(\beta\)) versus \(\sigma\): This panel shows a similar behaviour to the former one, being the correlation between the metallicity measured with Fe\(_{4383}\) and the velocity dispersion stronger for HDEGs. For the LDEGs, however, the relation is almost flat and even slightly negative.

- \([\text{M/H}]\) (Mgb–H\(\beta\)) versus \(\sigma\): The relation between the metallicity measured with Mgb and the velocity dispersion is rather similar for both subsamples of galaxies. Furthermore, we did not find any significant difference between the zero point of both relations; both samples are compatible with the same metallicity (as measured with Mgb) \(\sigma\) relation.

- Age versus \(\sigma\): In this panel it can be seen that, while for the HDEGs the relation is flat, there exists a correlation between the age and velocity dispersion for the LDEGs, in the sense that low velocity dispersion galaxies tend to be younger. This is in agreement with the suggestion by Trager et al. (2000b), who found differences in the \((\sigma, t)\) plane between galaxies in the field and in the Fornax cluster. Interestingly, Jørgensen (1999) did not find any correlation between age and velocity dispersion in her study of a sample of galaxies in the Coma cluster, although she found a considerable dispersion in the ages of the galaxies. Caldwell et al. (2003) also found younger ages for lower \(\sigma\) galaxies in a sample of Virgo galaxies and galaxies in lower environments. Thomas et al. (2004) did not find a significant trend between the age and the velocity dispersion in either their sample of high- or low-density environment galaxies. However, they argued that the correlated errors of age and metallicity tend to dilute a correlation between age and the velocity dispersion and that their observational data are best reproduced by a relatively flat, but significant correlation.

It is also clear from Fig. 2 that the age dispersion for less massive galaxies is higher than for the more massive ones, in agreement with other studies (e.g. Bender, Burstein & Faber 1993; Bressan, Chiosi & Tantalo 1996; Worthey 1996; Mehlert et al. 1998; Vazdekis & Arimoto
Table 1. Central ages and metallicities obtained in different index–index diagrams. The associated errors are indicated under the measurements. See text section 2 for more details.

| Galaxy    | log(age) | [M/H] | Mgb–Hα | Fe4383–Hα | Mgb–Hα | Fe4383–Hα | CN2–Hα | log(age) | [M/H] |
|-----------|----------|-------|--------|-----------|--------|-----------|--------|----------|-------|
| NGC 221  | 9.455    | 0.164 | 9.431  | 0.283     | 9.464  | 0.105     | 9.443  | 0.223    | -0.003 |
| NGC 315  | 9.913    | 0.517 | 9.913  | 0.517     | 9.931  | 0.411     | 10.066 | 0.079    |
| NGC 507  | 9.996    | 0.196 | 10.186 | -0.180    | 9.945  | 0.311     | 9.938  | 0.342    | 10.078 |
| NGC 584  | 9.818    | 0.129 | 0.169  | 0.223     | 0.077  | 0.150     | 0.105  | 0.091    | 0.038  |
| NGC 636  | 9.768    | 0.207 | 9.859  | 0.082     | 9.727  | 0.316     | 9.703  | 0.421    | 9.701  |
| NGC 821  | 9.714    | 0.299 | 9.733  | 0.215     | 0.162  | 0.125     | 0.161  | 0.111    | 0.046  |
| NGC 1600 | 9.935    | 0.300 | 10.075 | 0.014     | 9.807  | 0.442     | 10.094 | 0.120    |
| NGC 1700 | 9.706    | 0.283 | 9.725  | 0.193     | 0.162  | 0.126     | 0.160  | 0.107    | 0.042  |
| NGC 2300 | 9.905    | 0.289 | 9.943  | 0.101     | 9.869  | 0.438     | 9.927  | 0.136    |
| NGC 2329 | 10.153   | 0.127 | 9.955  | 0.445     | 10.122 | 0.168     | 9.923  | 0.060    |
| NGC 2693 | 10.173   | 0.197 | 9.988  | 0.435     | 10.027 | 0.357     | 9.988  | 0.131    |
| NGC 2694 | 9.931    | 0.162 | 10.029 | -0.059    | 9.638  | 0.399     | 9.920  | 0.212    | 9.726  |
| NGC 2778 | 9.704    | 0.288 | 9.737  | 0.134     | 9.569  | 0.452     | 9.561  | 0.512    | 10.016 |
| NGC 2832 | 9.949    | 0.334 | 10.138 | -0.027    | 9.913  | 0.515     | 9.764  | 0.474    | 9.988  |
| NGC 3115 | 9.923    | 0.297 | 10.050 | -0.002    | 9.906  | 0.402     | 9.752  | 0.399    | 9.931  |
| NGC 3377 | 9.715    | 0.084 | 9.712  | 0.097     | 9.562  | 0.341     | 9.560  | 0.359    | 9.950  |
| NGC 3379 | 9.914    | 0.172 | 9.974  | -0.024    | 9.894  | 0.287     | 9.865  | 0.405    | 9.935  |
|          | 0.033    | 0.059 | 0.059  | 0.046     | 0.104  | 0.109     | 0.119  | 0.163    | 0.046  |

As stated in Paper I, a decision was made to include the Virgo galaxies with the rest of the LDEGs in order to enlarge the number of galaxies in this group, as we did not find any difference between the stellar population of those two sub-samples. In further support of this decision, we have plotted, in Fig. 3, the relation of the ages with the velocity dispersion for galaxies in the Coma cluster, Virgo clusters and groups separately. In opposition with the behaviour of galaxies in the Fornax (Kuntschner 2000) and Coma cluster, galaxies in the Virgo cluster show a greater spread in the ages of their populations and they appear to be correlated with the velocity dispersion of the galaxies.

4. Simple stellar population or multiple bursts?

The new generation of stellar population models do not only predict individual features as a function of the age and metallicity, but synthesise full spectral energy distributions (SEDs) (Vazdekis 1999; Vazdekis et al. 2003; Bruzual & Charlot 2003; Le Borgne et al. 2004). This is possible thanks to the growing number of stellar libraries with a large number of stars (eg. Le Borgne et al. 2003; Valdes et al. 2004; Sánchez–Blázquez et al. 2006). To show the potential of these new models, in Fig. 6 we compare the spectral energy distribution of two galaxies, NGC 4467 and NGC 3605, with two synthetic spectra from V06 for a single population of age and metallicity as indicated in the panels. Both observed and synthetic spectra were normalised to 5000 Å. As can be seen, the coincidence is very good. The shape of both spectra (observed and synthetic) are real and their similarity gives support to the flux calibration of both the galaxies and the stellar spectra.

The age and metallicity values of the synthetic spectra that best reproduce the observed spectra were calculated by minimising the residual r.m.s. (obtained as the differences between the observed and the synthetic spectra in the region 3650–5150 Å). Internal reddening has not been taken into account in this analysis. The estimation of the synthetic spectra that best reproduce the observed is affected by the age–metallicity degeneracy, but synthise full spectral energy distributions (SEDs)
It is apparent from Fig. 6 that, for LDEGs, there is a significant difference between the ages obtained in the two different environments. This difference is more evident below 9100 Å, which is consistent with the different age ranges found for V06 models in two different environments. For LDEG and HDEG, the difference in the age distribution obtained in the two scenarios is carried out a comparison of the observed galaxy spectra with the synthetic spectra extracted from V06 models in two different wavelength ranges: 3650–4050 Å and 4750–5150 Å. The ages and metallicities were calculated combining the values of the 9 synthetic spectra that best reproduce the observed spectra in each wavelength interval, as explained above. Figs. 6 and 7 show the age distributions obtained in each wavelength range.

It has been seen in Sec. 3 that LDEGs span a broad range in their apparent mean ages and that, in some cases, these ages are very low. Since the models assume a unique burst of star formation, these low values can indicate either that these galaxies are genuinely young, that is, that they formed all their stars recently, or that most of their stars were formed at early epochs, but they have undergone later episodes of star formation involving a certain percentage of the total mass of the galaxy (see Trager et al. 2000b). In the latter case, the apparent mean age would depend on the relative light contributions of the different components to the considered spectral range. To distinguish between the two scenarios, we carried out a comparison of the observed galaxy spectra with the synthetic spectra extracted from V06 models in two different wavelength ranges: 3650–4050 Å and 4750–5150 Å. The ages and metallicities were calculated combining the values of the 9 synthetic spectra that best reproduced the observed spectra in each wavelength interval, as explained above. Figs. 6 and 7 show the age distributions obtained in both wavelength ranges for LDEG and HDEG respectively. It is apparent from Fig. 6 that, for LDEGs, there is a significant difference between the ages obtained in the two different regions of the spectra. This is difficult to understand if all the stars were formed in a single burst, and it suggests that many LDEGs are composite systems consisting of an underlying old population plus, at least, a later star formation burst.

Table 1. Continued.

| Galaxy | log(age) | [M/H] | log(age) | [M/H] | log(age) | [M/H] | log(age) | [M/H] | log(age) | [M/H] |
|--------|----------|-------|----------|-------|----------|-------|----------|-------|----------|-------|
| NGC 3605 | 9.512    | 0.227 | 9.521    | 0.144 | 9.514    | 0.210 | 9.925    | 0.012 |          |       |
| NGC 3608 | 9.926    | 0.176 | 10.011   | −0.033| 9.878    | 0.409 | 9.829    | 0.407 | 9.921    | 0.122 |
| NGC 3641 | 9.742    | 0.216 | 9.870    | −0.079| 9.723    | 0.292 | 9.702    | 0.392 | 10.105   | 0.107 |
| NGC 3665 | 10.105   | 0.014 | 10.159   | −0.131| 9.967    | 0.251 | 10.003   | 0.181 | 9.910    | 0.045 |
| NGC 3818 | 9.761    | 0.218 | 9.870    | 0.018 | 9.729    | 0.310 | 9.597    | 0.444 | 10.077   | 0.099 |
| NGC 4261 | 9.709    | 0.423 | 9.879    | 0.075 | 0.147    | 0.117 | 0.083    | 0.065 | 0.039    | 0.033 |
| NGC 4278 | 10.095   | 0.152 | 9.931    | 0.500 | 9.968    | 0.372 | 10.066   | 0.079 |          |       |
| NGC 4365 | 9.900    | 0.344 | 9.978    | 0.040 | 9.881    | 0.414 | 10.100   | 0.139 |          |       |
| NGC 4374 | 10.054   | 0.118 | 10.148   | −0.069| 9.925    | 0.429 | 9.941    | 0.354 | 10.017   | 0.099 |
| NGC 4415 | 9.855    | −0.146| 9.893    | −0.256| 9.841    | −0.103| 9.751    | −0.424|          |       |
| NGC 4431 | 10.001   | −0.408| 9.972    | −0.264| 9.973    | −0.270| 9.955    | −0.483|          |       |
| NGC 4464 | 10.057   | −0.060| 10.096   | −0.154| 9.943    | 0.164 | 9.929    | 0.223 | 9.846    | 0.115 |
| NGC 4467 | 9.993    | 0.027 | 10.043   | −0.063| 9.934    | 0.171 | 9.917    | 0.254 | 9.851    | 0.116 |
| NGC 4472 | 9.894    | 0.220 | 10.072   | 0.068 | 9.935    | 0.355 | 9.921    | 0.429 | 10.098   | 0.139 |
| NGC 4478 | 9.874    | 0.055 | 9.885    | −0.020| 9.878    | 0.029 | 9.851    | 0.199 | 9.699    | 0.093 |
| NGC 3379 | 9.914    | 0.172 | 9.974    | −0.024| 9.894    | 0.287 | 9.865    | 0.405 | 9.935    | 0.129 |
| NGC 3605 | 9.512    | 0.227 | 9.521    | 0.144 | 9.514    | 0.210 | 9.925    | 0.012 |          |       |
| NGC 3608 | 9.926    | 0.176 | 10.011   | −0.033| 9.878    | 0.409 | 9.829    | 0.407 | 9.921    | 0.122 |
| NGC 3641 | 9.742    | 0.216 | 9.870    | −0.079| 9.723    | 0.292 | 9.702    | 0.392 | 10.105   | 0.107 |
| NGC 3641 | 9.742    | 0.216 | 9.870    | −0.079| 9.723    | 0.292 | 9.702    | 0.392 | 10.105   | 0.107 |
| NGC 3641 | 9.742    | 0.216 | 9.870    | −0.079| 9.723    | 0.292 | 9.702    | 0.392 | 10.105   | 0.107 |
| NGC 3641 | 9.742    | 0.216 | 9.870    | −0.079| 9.723    | 0.292 | 9.702    | 0.392 | 10.105   | 0.107 |
To study this in more detail, we have built different composite spectra in which we have added to an old population of 15.85 Gyr and metallicity [M/H]=−0.38 dex, different components of metallicity [M/H]=+0.2 and ages ranging from 2.51 to 14.12 Gyr. The percentages of these two components were chosen to be 70 and 30% (model 1, solid line), 80 and 20% (model 2, dashed line), and 90 and 10% (model 3, dotted line) in mass, respectively. Fig. 8 shows the relation between the derived ages in these two spectral ranges for different models and, over-plotted, the derived ages for the LDEGs (crosses). As can be seen, although it is difficult to match the observed points with single scenarios, as the contribution in mass and the look-back time of the star formation event are highly degenerate, the combination of an old population and a burst of star formation would lead to similar trends in the derived ages as the observed for the LDEGs. We also note that, in order to reproduce the observed trends, the metallicity of the young component must be higher than the metallicity of the underlying old population, in agreement with the findings of other authors (eg. Ferreras, Charlot & Silk 1999; Trager et al. 2000a; Thomas et al. 2004).

We note here that the differences between the ages derived in the two spectral ranges do not follow simple relation. The shape of this relation depends on the difference in light contributions of the burst to the considered wavelength regions. Table 3 shows these fractions, as calculated in model 2. It can be noted that the contribution of the young population is higher in the red wavelength range than in the blue when its age become older than 3.5 Gyr. This is due to the larger metallicity of the young component with respect to the subyacent population. In a model where both, subyacent population and burst have the same metallicity, the contribution of the young component to the total light is always larger in the bluer wavelengths. Figure 8 shows the relation of the differences in the light fraction of the burst between the two considered spectral regions, and the
age of the burst, also calculated for model 2. As can be seen, the differences are larger for older bursts (although the trend is not monotonic). That is the reason why the differences between the ages calculated in two different spectral ranges increase with the age of the burst.

On the other hand, the distribution of ages for HDEGs (Fig. 7) shows no such a clear dichotomy (see mean values in the insets). This is compatible with the idea that these galaxies constitute a more homogeneous (coeval) sample which have undergone their last episode of star formation at higher redshift. This interpretation is in agreement with our findings in Sánchez–Blázquez et al. (2003) and in Paper I.

### 5. The age–metallicity relation

Several authors have noted that when the age and metallicity obtained from an index–index diagram are plotted together, they show a correlation in the sense that younger galaxies seem to be also more metal rich (e.g. Trager et al. 1998; Jørgensen 1999; Ferreras et al. 1999; Trager et al. 2000b; Terlevich & Forbes 2002). This age–metallicity relation is difficult to explain under the hypothesis of passive evolution and high formation ages. However, this relation is expected if, during their evolution, galaxies have undergone several episodes of star formation, in which the new stars formed from pre-enriched gas by the previous generations of stars. Furthermore, the existence of an age–metallicity relation has implications in the interpretation of the scale-relations. The low dispersion in the Mg$_{II}$–σ or the color–magnitude relations, and the existence of a fundamental plane have been common arguments in favor of the hypothesis that elliptical galaxies are old systems which formed all their stars at high redshift and evolved passively since then (Bender, Burstein & Faber 1993; Bernardi et al. 1998). However, some authors, (e.g. Trager et al. 1998, 2000b; Ferreras et al. 1999; Jørgensen 1999) have studied the scale rel-

---

| Galaxy     | log(age) | [M/H] | log(age) | [M/H] | log(age) | [M/H] | log(age) | [M/H] | log(age) | [M/H] | log(age) | [M/H] |
|------------|----------|-------|----------|-------|----------|-------|----------|-------|----------|-------|----------|-------|
| NGC 4673   | 9.577    | 0.297 | 9.722    | 0.090 | 9.556    | 0.434 | 9.552    | 0.465 | 9.891    | 0.059 |
| NGC 4692   | 9.908    | 0.305 | 9.948    | 0.112 | 9.872    | 0.456 | 9.726    | 0.457 | 9.984    | 0.131 |
| NGC 4697   | 9.770    | 0.197 | 9.833    | 0.138 | 9.780    | 0.186 | 9.599    | 0.428 | 10.042   | 0.108 |
| NGC 4742   | 9.018    | 0.489 | 9.115    | 0.368 | 9.021    | 0.131 | 0.997    | 0.046 | 0.044    | 0.033 |
| NGC 4839   | 9.732    | 0.423 | 9.915    | 0.241 | 9.732    | 0.425 | 9.911    | 0.126 | 0.064    | 0.075 |
| NGC 4842A  | 9.925    | 0.327 | 10.087   | 0.024 | 9.904    | 0.460 | 9.945    | 0.239 | 9.953    | 0.120 |
| NGC 4842B  | 9.934    | 0.189 | 9.984    | 0.060 | 9.659    | 0.402 | 9.947    | 0.139 | 9.783    | 0.113 |
| NGC 4875   | 9.922    | 0.182 | 10.050   | 0.123 | 9.732    | 0.419 | 9.920    | 0.196 | 9.973    | 0.122 |
| NGC 4864   | 9.885    | 0.272 | 9.952    | 0.029 | 9.867    | 0.348 | 9.892    | 0.236 | 9.852    | 0.077 |
| NGC 4865   | 9.726    | 0.340 | 9.888    | 0.023 | 9.586    | 0.513 | 9.723    | 0.353 | 9.830    | 0.128 |
| NGC 4867   | 9.720    | 0.294 | 9.845    | 0.039 | 9.572    | 0.517 | 9.700    | 0.387 | 9.805    | 0.012 |
| NGC 4874   | 9.923    | 0.253 | 9.963    | 0.109 | 9.893    | 0.416 | 9.818    | 0.411 | 9.883    | 0.133 |
| NGC 4889   | 9.963    | 0.302 | 10.190   | 0.121 | 9.912    | 0.523 | 9.752    | 0.474 | 9.988    | 0.131 |
| NGC 4908   | 9.977    | 0.077 | 10.086   | 0.135 | 9.910    | 0.323 | 9.954    | 0.123 | 9.923    | 0.091 |
| NGC 5638   | 9.715    | 0.232 | 9.744    | 0.104 | 9.591    | 0.337 | 9.565    | 0.477 | 9.843    | 0.147 |
| NGC 5796   | 9.852    | 0.235 | 9.872    | 0.120 | 9.582    | 0.542 | 9.588    | 0.515 | 9.942    | 0.145 |
| NGC 5812   | 9.728    | 0.310 | 9.843    | 0.144 | 9.705    | 0.413 | 10.037   | 0.128 | 0.045    | 0.032 |
| NGC 5813   | 9.741    | 0.242 | 9.855    | 0.036 | 9.704    | 0.403 | 9.575    | 0.537 | 10.084   | 0.110 |
| NGC 5831   | 9.543    | 0.316 | 9.556    | 0.226 | 9.541    | 0.331 | 9.511    | 0.516 | 9.937    | 0.127 |
| 0.130      | 0.160    | 0.032 | 0.048    | 0.089 | 0.164    | 0.041 | 0.203    | 0.046 | 0.031    |
relationships showing that a possible age–metallicity degeneracy would constitute a conspiracy to preserve the low dispersion in those relationships even when a relatively large fraction of galaxies contain young stars.

Fig. 10 shows this correlation for LDEGs when the age and metallicity are derived from a Fe4383–Hβ diagram. It is clear from this diagram that younger galaxies do appear to be also more metal rich. However, when age and metallicity are measured in a partially degenerated index–index diagram, the correlation of the errors in both parameters tend to create an artificial anti-correlation between them (Kuntschner et al. 2001), so it is difficult to disentangle if the relation is real or an artifact due to the age-metallicity degeneracy. To check if the correlation of the errors could be the reason for the observed trend in our sample, we carried out a similar test to that performed by Kuntschner et al. (2001). We chose to model three different population with the following characteristics:

1: Population with a single age of 8 Gyr and solar metallicity.
2: Population with a single age of 8 Gyr and metallicity ranging from 0.00 < [M/H] < 0.06.
3: Population with a range of ages between 5.6 and 10 Gyr, and solar metallicity.

measured the Fe4383 and Hβ in these three populations and tried to reproduce the dispersion due to errors in this index–index diagram through Monte Carlo simulations. To do that, each point was perturbed with our typical observed error, following a Gaussian distribution. Fig. 11 shows the index–index diagrams for 10000 Monte Carlo realizations of the 3 populations (small dots). The model predictions from V06 are also plotted. The age and metallicities obtained by interpolating in the diagrams for the three different populations are represented in the bottom panels of Fig. 11 (small dots). The grey circles represent the observed values in LDEGs.

| Galaxy      | log(age) | [M/H] | log(age) | [M/H] | log(age) | [M/H] | log(age) | [M/H] | log(age) | [M/H] |
|-------------|----------|-------|----------|-------|----------|-------|----------|-------|----------|-------|
| NGC 5845    | 9.919    | 0.172 | 9.984   | −0.018 | 9.917    | 0.183 | 9.723    | 0.445 | 10.065   | 0.112 |
| NGC 5846    | 9.926    | 0.219 | 10.029  | −0.025 | 9.737    | 0.421 | 9.884    | 0.429 | 10.049   | 0.103 |
| NGC 5846A   | 10.029   | 0.061 | 0.089   | 0.079  | 0.134    | 0.087 | 0.070    | 0.142 | 0.044    | 0.033 |
| NGC 6127    | 9.927    | 0.273 | 10.004  | 0.072  | 9.881    | 0.496 | 9.734    | 0.453 | 9.925    | 0.136 |
| NGC 6166    | 9.989    | 0.536 | 10.197  | 0.310  | 9.948    | 0.477 | 9.925    | 0.304 | 10.047   | 0.033 |
| NGC 6411    | 9.718    | 0.252 | 9.723   | 0.228  | 9.589    | 0.378 | 9.576    | 0.447 | 10.104   | 0.107 |
| NGC 6482    | 10.040   | 0.445 | 10.162  | 0.364  | 10.058   | 0.116 | 10.037   | 0.035 | 10.047   | 0.033 |
| NGC 6577    | 9.947    | 0.279 | 10.137  | −0.107 | 9.913    | 0.448 | 9.936    | 0.326 | 9.953    | 0.116 |
| NGC 6702    | 9.211    | 0.451 | 0.233   | 0.067  | 0.130    | 0.094 | 0.046    | 0.031 | 0.045    | 0.031 |
| NGC 6703    | 9.745    | 0.092 | 9.721   | 0.197  | 9.776    | 0.012 | 9.570    | 0.442 | 9.945    | 0.125 |
| NGC 7052    | 10.073   | 0.996 | 0.038   | 0.032  | 0.045    | 0.102 |
| IC 767      | 9.397    | −0.478| 9.344   | −0.107 | 9.395    | −0.468| 9.279    | −0.240| 9.279    | −0.240|
| IC 794      | 9.731    | −0.184| 9.581   | 0.083  | 9.774    | −0.413| 9.807    | 0.442 | 9.788    | −0.072|
| IC 832      | 9.797    | 0.091 | 9.889   | −0.161 | 9.720    | 0.290 | 9.827    | 0.026 | 9.756    | −0.066|
| IC 3957     | 9.957    | 0.108 | 10.009  | 0.111  | 9.743    | 0.400 | 9.915    | 0.280 | 10.150   | 0.162 |
| IC 3959     | 9.733    | 0.324 | 9.895   | −0.003 | 9.703    | 0.455 | 10.083   | 0.112 | 10.083   | 0.112 |
| IC 3963     | 9.721    | 0.211 | 9.737   | 0.141  | 9.591    | 0.347 | 9.727    | 0.187 | 9.837    | 0.021 |
| IC 3973     | 9.569    | 0.342 | 9.595   | 0.211  | 9.546    | 0.502 | 9.547    | 0.500 | 9.834    | 0.133 |
|             | 0.103    | 0.061 | 0.111   | 0.085  | 0.033    | 0.048 | 0.041    | 0.204 | 0.046    | 0.030 |

Table 1. Continued.
in 1000 different environments. The er-

\[ \text{log(age) } [\text{MgFe} - \text{H}_\beta] \]

\[ \text{log(age) } [\text{Fe}4383 - \text{H}_\beta] \]

\[ \text{log(age) } \text{Mg} - \text{H}_\beta \]

\[ \text{log(age) } \text{CN}_2 - \text{H}_\beta \]

\[ \text{log(age) } \text{spectral synthesis} \]

| Galaxy | log(age) | [M/H] | log(age) | [M/H] | log(age) | [M/H] | log(age) | [M/H] | log(age) | [M/H] | log(age) | [M/H] |
|--------|----------|-------|----------|-------|----------|-------|----------|-------|----------|-------|----------|-------|
| IC 4026 | 9.723 | 0.270 | 9.825 | 0.021 | 9.707 | 0.347 | 9.773 | 0.128 | 10.149 | 0.149 | 0.259 | 0.223 |
| IC 4042 | 10.216 | 0.188 | 10.151 | 0.152 | 10.194 | 0.141 | 10.149 | 0.028 | 0.194 | 0.141 | 0.149 | 0.149 |
| IC 4051 | 9.965 | 0.315 | 9.912 | 0.540 | 9.921 | 0.489 | 9.991 | 0.130 | 0.152 | 0.149 | 0.149 | 0.149 |
| CGCG 159-41 | 10.112 | 0.089 | 0.034 | 0.056 | 0.038 | 0.043 | 0.041 | 0.030 | 0.112 | 0.141 | 0.047 | 0.073 |
| CGCG 159-43 | 9.994 | 0.188 | 10.144 | -0.112 | 9.915 | 0.451 | 9.919 | 0.427 | 10.148 | 0.155 | 0.106 | 0.095 |
| CGCG 159-83 | 10.053 | 0.061 | 10.101 | 0.144 | 0.061 | 0.067 | 0.068 | 0.067 |
| CGCG 159-89 | 9.573 | 0.258 | 9.704 | 0.122 | 9.558 | 0.352 | 9.559 | 0.343 | 10.101 | 0.144 | 0.219 | 0.145 |
| DRCG 27-032 | 10.187 | -0.137 | 10.177 | -0.119 | 10.014 | -0.143 | 0.225 | 0.650 | 0.061 | 0.067 |
| DRCG 27-127 | 9.703 | 0.323 | 9.784 | 0.052 | 9.572 | 0.471 | 9.762 | 0.097 | 10.106 | 0.108 | 0.172 | 0.141 |
| DRCG 27-128 | 9.585 | 0.157 | 9.580 | 0.181 | 9.556 | 0.320 | 9.960 | 0.092 | 0.154 | 0.121 |
| GMP 3121 | 10.104 | -0.247 | 9.964 | 0.064 | 10.115 | -0.291 | 9.610 | -0.050 | 0.222 | 0.381 |
| GMP 3196 | 9.936 | -0.339 | 9.856 | -0.088 | 9.874 | -0.138 | 9.655 | -0.325 | 0.284 | 0.229 |
| MCG+05-31-63 | 10.053 | -0.061 | 10.130 | -0.291 | 9.933 | 0.196 | 9.920 | -0.107 | 0.142 | 0.214 |
| PGC 126756 | 9.957 | -0.507 | 9.905 | -0.314 | 9.969 | -0.552 | 9.656 | -0.329 | 0.176 | 0.363 |
| PGC 126775 | 9.411 | -0.275 | 9.380 | -0.061 | 9.396 | -0.163 | 9.307 | 0.311 | 9.559 | -0.369 | 0.249 | 0.387 |
| RB 91 | 9.873 | 0.127 | 9.880 | 0.084 | 9.726 | 0.353 | 9.880 | 0.086 | 10.151 | 0.152 | 0.190 | 0.154 |
| RB 113 | 10.153 | 0.156 | 0.029 | 0.028 | 0.029 | 0.028 | 0.029 | 0.028 |

Table 2. Slopes of the linear fits (b) and their errors (\(\Delta b\)) of the different parameters in Fig. 2 with the central velocity dispersion. The left side of the table show the values for the LDEGs, while the right side of the table, the values for the HDEGs. The last two columns show the result of a t-test to verify if the slopes of both subsamples of galaxies are different. In particular, the last column shows the probability that the slopes of HDEGs and LDEGs are different by chance.

| LDEG | HDEG |
|------|------|
| \(b\) | \(\Delta b\) | \(t\) | \(\alpha\) |
| \([M/H] (CN_2)\) | 0.00037 | 0.00034 | 0.00138 | 0.00065 | 1.37 | 9% |
| \([M/H] (Fe4383)\) | -0.00050 | 0.00030 | 0.00085 | 0.00053 | 2.21 | 1% |
| \([M/H] (Mgb)\) | 0.00113 | 0.00031 | 0.00077 | 0.00042 | 0.69 | 24% |
| log (age) | 0.00177 | 0.00033 | 0.00004 | 0.00064 | 2.41 | 1% |

We then performed a linear fit to quantify the slope of the relations in both, the fake distributions and the galaxies. The errors in the slope were estimated using Monte Carlo simulations in which we generated \(N\) elements, \((N\) being the number of points), where some data appear duplicated and others not. The final error was obtained as the standard deviation of the slopes in 1000 different simulations. The final results are shown in Table 2. We performed a \(t\) test to check whether the slopes of the simulations were compatible with the slope of the LDEGs data. A \(t\) value higher than 1.96 allows us to reject the hypothesis of equal slopes with a significance level lower than 0.05. As can be seen, the slopes defined by the populations 2 and 3 are not compatible with the slope of LDEGs. However, the slope obtained for the first distribution of constant age and metallicity is marginally compatible with the one obtained from the data (although the probability that the slopes are different is > 95%). Nevertheless, none of the three models can reproduce the dispersion in age and metallicity observed in the sample of
Fig. 2. Relations between metallicities, obtained with different indicators, and age against velocity dispersion for the sample of galaxies. Open symbols represent galaxies in low-density environments (LDEGs), while filled symbols indicate galaxies in high density environments (HDEGs). Squares correspond to S0 galaxies while elliptical galaxies are represented with circles. Grey and black lines show the linear fit, weighting with the errors in both axes, to the LDEGs and HDEGs respectively.

Fig. 11. Top panels: index–index diagrams for 3 different fake populations with the following characteristics: From left to right, (1) Age 8 Gyr and solar metallicity [M/H]=0; (2) Age 8 Gyr and metallicity between 0.0< [M/H] < 0.06; (3) Age between 5.6 and 10 Gyr and solar metallicity [M/H]=0. Small dots represent the results of Monte Carlo simulations in which each point was perturbed following a Gaussian distribution with standard deviation given by the typical error in Fe4383 and Hβ indices in the sample of LDEGs. Bottom panels: Age-metallicity relation for each of the 3 fake distributions plotted on the upper panels. Dashed lines show the linear fit to these distributions. Grey circles show the age and metallicity for LDEGs and the solid lines represent the linear fit to these data.

LDEGs. We then conclude that, although the correlation of the errors can explain the existence of an age–metallicity relation in a distribution of galaxies with constant age and metallicity, it cannot explain the observed dispersion in these parameters. If we try to reproduce the dispersion by simulating populations with a range in age or metallicity, the slope of the relation does not reproduce the slope obtained for the real galaxies. This indicates that part of the relation has to be real, and not only a consequence of the correlation of errors, although the actual value of the slope can be modified by this effect.

Another way to verify if the relation is an artifact of the error correlations is to represent the age versus the metallicity obtained in two completely independent index–index diagrams. Fig. 12 shows the age–metallicity relation where the ages have been measured in a Hβ–Fe4531 diagram and the metallicities in a HδF–Fe4383 diagram. A non-parametric Spearman rank-
order correlation test gives a correlation coefficient of $-0.47$ corresponding to a significance level of 0.0002. Although the slope of the relation is flatter ($-0.237 \pm 0.076$) than the one obtained by measuring the ages and metallicities in a Fe4383–Hβ diagram, there is still a significant correlation, which confirms that the age-metallicity relation is not entirely due to the correlation of the errors in both parameters.

The age–metallicity relation for HDEGs is plotted in Fig. 3 (see also Table 4). For comparison, we have also plotted the relation for the LDEGs (dashed line). As can be seen, the relation for HDEGs seems to be slightly flatter than for the LDEGs, although a $t$-test does not allow us to discard the possibility that they are equal within the errors. However, in Paper I we showed that in order to explain the relation of the indices with $\sigma$ for the HDEGs a variation of the age along the mass sequence was not necessary. Thus, if the age-metallicity relation is a consequence of recent star formation events (in which the younger stars have been formed from a more enriched gas), we would not expect to find this age–metallicity relation for the HDEGs.

To verify if the results obtained here are compatible with the relations of the indices with $\sigma$ reported in Paper I, we carried out the following experiment:
Table 4. Slopes of the age--metallicity relation calculated in the Fe4383–Hβ diagram for the three described distributions (see text), and for the LDEGs and HDEGs. The last two columns shows the dispersion in age and metallicity for the different distributions and the subsamples of observed galaxies.

| Distribution | Age(Gyr) | [M/H] | slope  | t   | σ_{log(age)} | σ_{[M/H]} |
|--------------|----------|-------|--------|-----|--------------|-----------|
| 1            | 8.00     | 0.06  | -0.668 ± 0.005 | 2.00 | 0.084        | 0.073     |
| 2            | 8.00     | 0.00–0.06 | -0.683 ± 0.005 | 2.37 | 0.084        | 0.076     |
| 3            | 5.62–10.00 | 0.00 | -0.362 ± 0.004 | 5.41 | 0.113        | 0.069     |
| LDEG         | -0.516 ± 0.044 | 0.255 | 0.152 |
| HDEG         | -0.333 ± 0.152 | 0.181 | 0.152 |

Fig. 6. Distribution of ages obtained comparing the synthetic spectra from V06 with the spectral energy distribution of LDEGs. The empty histogram show the ages obtained with the comparison in the spectral range 4750–5150 Å while the shaded histogram, the ages obtained comparing the region from 3650–4050 Å.

— We calculated pairs of indices from the indices-σ relations obtained in Paper I at a variety of sigma sampling from σ = 50km^{-1} to σ = 300kms^{-1} in intervals of constant velocity dispersion. Then, we measured the age and metallicities of these fake distribution of indices. We did not try to reproduce the observed distribution, i.e. the number of points in each σ-bin, but just the slope of the relation.

— To measured the ages and metallicities of this mock sample we use a Fe4383–Hβ diagram, obtaining the age--metallicity relation defined by the index–σ relations. The indices for each simulated point were then perturbed with the observational error adopting a Gaussian probability distribution, and an age--metallicity relation for the resultant distribution was also derived.

The age--metallicity relations obtained in this way are plotted in Fig. 14. We analyse the results obtained for LDEG and HDEG separately:

— LDEG: The age--metallicity relation obtained for the galaxies following the index–σ relation has an slope of 0.26 × 10^{-5} ± 10^{-5}. This value is lower than the slope of the real data but the probability that it is significantly different than zero is higher than 99%. Interestingly, the slope obtained in this way is similar to the slope obtained with two independent diagrams (−0.237 ± 0.076). We can consider this slope to be more representative of the real slope of the age--metallicity relation.

— HDEG: For this sample of galaxies, there is no age--metallicity relation for the points following the index–σ relations. However, when we add the errors, we obtain an artificial age--metallicity relation with a slope of −0.403 ± 6 × 10^{-5}, compatible, within the errors, with the slope obtained for the galaxies in this subsample.

Therefore, we conclude that a real relation between age and metallicity does exist (i.e. younger galaxies tend to be also more metal rich) for the LDEGs. On the other hand, HDEGs do not follow this relation, and the age-metallicity relation shown in Fig. 13 is probably a consequence of the correlation of the errors. In fact, when we measure the age and metallicity of the HDEGs in two independent diagrams (Fig. 15) we do not find any correlation between both parameters (the non-parametric Spearman rank order coefficient is 0.039 with a significance level of 0.422). The differences in the age--metallicity relation between LDEGs and HDEGs cannot be a consequence of differences in the luminosity range of the different samples, because the luminosity coverage of HDEGs is somewhat broader than those of LDEGs. A sample biased toward high-σ galaxies could also make the age-metallicity relation appear flatter, as
there is some evidence that the age dispersion is higher in the range of low-σ galaxies (Poggianti et al. 2001b; Caldwell et al. 2003). The sample of HDEGs, however, is biased towards low-σ galaxies compared with the LDEGs (see Paper I).

6. Discussion

In this section we will try to explain all the trends found in the previous sections with a common scenario. The results presented in this paper and in Paper I indicate that HDEGs constitute a more homogenous family than LDEGs; their stellar populations can be explained under the hypothesis of a single population and they are, on average, older. In Fig. 2 it has been shown that this subsample of galaxies exhibits a relation between the metallicity and the velocity dispersion, no matter which indices are used to derive this parameter, but, on the contrary, there is not age variation with velocity dispersion. For LDEGs, however, the age dispersion is higher and their populations are best explained as a composition of different bursts of star formation.

The hierarchical clustering models of structure formation predict different star formation histories for galaxies situated in different environments (Baugh et al. 1996; Kauffmann & Charlot 1998; de Lucia et al. 2006). In these models, clusters of galaxies are formed from the highest peaks in the primordial density fluctuations. It is where the merging of dark matter haloes, which contained the first galaxies, leads to galaxies dominated by a bulge at high redshifts (z ≥ 2). The mergers of galaxies and the acquisition of cold gas cannot continue once the relative velocity dispersion between galaxies is higher than 500 km s⁻¹, which makes the occurrence of further star formation episodes in these galaxies more difficult. This truncated star formation history also explains the higher [Mg/Fe] found in

Table 3. Fraction of light contributed by a burst of star formation with metallicity $Z = +0.2$ and strength of 20% in mass, in a galaxy with an age 15.85 Gyr and metallicity $Z = -0.38$ for different ages of the burst.

| Age burst(Gyr) | fb (3650-4050 Å) | fb (4750-5150 Å) |
|---------------|-----------------|-----------------|
| 1.00          | 0.956           | 0.932           |
| 1.12          | 0.944           | 0.917           |
| 1.26          | 0.932           | 0.904           |
| 1.41          | 0.920           | 0.896           |
| 1.58          | 0.900           | 0.879           |
| 1.78          | 0.882           | 0.817           |
| 2.00          | 0.811           | 0.766           |
| 2.24          | 0.766           | 0.712           |
| 2.51          | 0.712           | 0.685           |
| 2.82          | 0.653           | 0.634           |
| 3.16          | 0.596           | 0.588           |
| 3.55          | 0.544           | 0.547           |
| 3.98          | 0.482           | 0.463           |
| 4.47          | 0.403           | 0.404           |
| 5.01          | 0.398           | 0.309           |
| 5.62          | 0.343           | 0.362           |
| 6.31          | 0.284           | 0.307           |
| 7.08          | 0.246           | 0.268           |
| 7.98          | 0.193           | 0.217           |
| 8.91          | 0.161           | 0.188           |
| 10.00         | 0.135           | 0.162           |
| 11.22         | 0.110           | 0.140           |
| 12.59         | 0.084           | 0.109           |
| 14.12         | 0.070           | 0.093           |
HDEGs with respect to the values in younger looking LDEGs (Paper I).

On the other hand, the star formation in LDEGs has probably extended over a longer period of time, due to the occurrence of more star formation events or due to a longer single episode of star formation. This scenario was proposed to explain the differences between N, and maybe C, when comparing galaxies in different environments (Sánchez-Blázquez et al. 2003, Paper I).

We speculate that LDEGs and HDEGs could have initially presented similar relations between the metallicity and the velocity dispersion after their first massive star formation episode. However, if LDEGs have suffered subsequent episodes of star formation, the original correlation between metallicity and potential well (or mass) could have been erased, since other processes could have also played a role in defining the final metal content of the galaxies. The new stars, formed in the more recent events, would do it from a gas more enriched in the elements produced by low- and intermediate-mass stars, due to the higher active evolution timescale of these galaxies. If these star formation processes have had a greater relative influence (a larger ratio between the burst strength and the total galaxy mass) in less massive galaxies, as suggested by the age–σ relation, this would destroy the original relation between mass and metallicity (increasing Fe, C and N in low velocity dispersion galaxies). Furthermore, this would result in a relation between age and metallicity (as inferred from Fe features) in LDEGs, but not in HDEGs, as it is found in this paper. Another possibility is that less massive galaxies had actually experienced a more extended star formation history than more massive galaxies (Chiosi & Carraro 2002). This latter possibility is favoured by some recent studies that found a depletion in the luminosity function of red galaxies towards the faint end (Small et al. 2001; de Lucia et al. 2004).
Fig. 16. Age–metallicity relation for the sample of low-density environment galaxies when these parameters are measured in a Mgb–Hβ diagram. The line indicates a least square fit to the data, minimizing the residuals in both directions x and y.

Other authors have found differences between the mass–metallicity relation of galaxies in different environments. Trager et al. (2000b) found that there is a velocity dispersion–metallicity relation for old cluster galaxies, but no comparable relation exists for field ellipticals. This result is compatible with ours, with the difference that we still find a steep relation between the metallicity and the velocity dispersion for LDEGs when the metallicity is measured with Mgb. Actually, Trager et al. also found a relation between what they called the enhanced elements (including Mg) and velocity dispersion for all the galaxies in their sample.

If, as we have argued, the age–metallicity relation is a consequence of later episodes of star formation, and the relative enrichment have been more pronounced in the Fe-peak elements, we would expect differences in the age-metallicity relation when the metallicity is measured using an index with a different sensitivity to changes in Fe and Mg. Fig. 16 shows the age–metallicity relation when these parameters are measured in a Mgb–Hβ diagram. The non-parametric rank order coefficient is 0.177 with a significance level of 0.10. Certainly, there is not a significant correlation between these two parameters when the Mg index is used instead of Fe4383. We need to stress again that we are not calculating chemical abundances in this paper. The metallicity measure with Mgb does not correspond to the abundance of Mg, and neither the metallicity measured with Fe4383, an Fe abundance. We argue though, that the different behaviours of the metallicities calculated with different indices are the consequence of their different sensitivities to variation of different chemical species. In this specific case, the flatter slope of the age-metallicity relation when a more (less) sensitive Mg (Fe) index is used is in agreement with our scenario.

Interestingly, the more massive galaxies in low density environments show a behaviour very similar to the massive galaxies of the Coma cluster. These very massive galaxies tend to have boxy isophotes, which can be explained by models of mergers without gas (Binney & Petrou 1985; Bender & Möllenhoff 1987; Nieto & Bender 1989; Nieto et al. 1991; Bender, Burstein & Faber 1992; Faber et al. 1997; Lauer et al. 2005), since a few percent of the mass in gas is sufficient to destroy boxy orbits and impart high global rotation (Barnes 1996; Barnes & Hernquist 1996). Furthermore, boxy galaxies tend to have cores inner profiles (Faber et al. 1997). N-body simulations of merging galaxies with central black holes (Ebisuzaki, Makino & Okumura 1991; Makino 1997; Quinlan & Hernquist 1997; Milosavljević & Merritt 2001) show that one can indeed form in such merger remnants. Recently, Lauer et al. (2005) have found that power-law galaxies, on average, have steeper colour gradients than do core galaxies (although the difference is small). This result is compatible with the idea that power-law galaxies have formed in gas-rich mergers while core galaxies have formed from free-gas mergers, which would cause a dilution in the metallicity gradient. Actually, these mergers without gas have been observed in clusters at $z = 0.8$ (van Dokkum et al. 1999). The existence of these gas-free mergers indicates that the epoch of assembly does not necessarily coincide with the epoch of formation of the bulk of stars. This scenario could bring into agreement the hierarchical models of galaxy formation with the observed trends of age with mass for elliptical galaxies in LDEGs. These trends (low-$\sigma$ galaxies appearing to be younger) are completely opposite to what is expected under these scenarios of galaxy formation, that predict that larger galaxies assemble at later times than small ones (Kauffmann, White & Guiderdoni 1993). However, these predictions are made under the assumption that all the gas cooled off and formed stars when the haloes were assembled. However, other processes such as supernova feedback may play a role in regulating the rate at which stars form in these systems (e.g. Kawata & Gibson 2003). Several mechanisms have been proposed to explain the apparent that low-mass galaxies have suffered a more extended star formation history. Kawata (2001) suggests that UV background radiation is a possible candidate, because it suppresses cooling and star formation more strongly in lower mass systems (Efstathiou 1992), and is expected to extend the duration of star formation. Chiosi & Carraro (2002) have recently build N-body-tree-SPH simulations incorporating cooling, star formation, energy feedback and chemical evolution. These authors find that the star formation history is governed by the initial density and total mass of the galaxy, and that the interplay of the above processes results in a more extended star formation history in low-mass galaxies. Until we understand completely the role of these mechanisms, we will not be able to rule out different processes of galaxy formation.

7. Conclusions

We have studied the stellar population properties of the centers of 98 early-type galaxies spanning a large range in velocity dispersion. Using the new stellar population synthesis models of V06, which include a new and improved stellar library (MILES), we have derived ages and metallicities for this sample of galaxies. Due to the difficulties in deriving chemical abundances with the available tools, we have studied the behaviour of the different chemical elements in a very qualitative way, measuring the metallicity with different indices especially...
sensitive to different chemical species. From this analysis, we conclude:

- The sample of LDEGs spans a wide range in SSP-equivalent ages and metallicities. This confirms previous results obtained by other authors (e.g. González 1993; Trager et al. 1998; Trager et al. 2000b). This age spread is not meant to imply that galaxies formed all their stars at different epochs. In fact, we have shown that galaxies in low density environments are best explained as a composition of populations in which a low percentage of young stars is added to an old population, in agreement with the conclusions of Trager et al. (2000b).

- For the subsample of LDEGs, there is a relation between the age and the velocity dispersion in the sense that less massive galaxies tend to be younger. This “down-sizing effect” suggests either that the episodes of star formation have had a larger relative influence on the low mass galaxies, or that the last star formation activity occurs on average at lower redshifts for progressively fainter galaxies. This relation is also present for galaxies in the Virgo cluster, but it is not present in the subsample of galaxies in the Coma cluster.

- Comparing the ages obtained in different regions of the spectra we have shown that galaxies in low-density environments are best described by a composition of populations in which an small percentage of young stars are added to an old population. On the other hand, the population of the HDEGs can be described with a single burst, which does not necessarily indicate that these galaxies formed all their stars in a single burst, but may indicate that the last episode of star formation finished at earlier times than in LDEGs.

- The sample of LDEGs shows a relation between the age and the metallicity implying that younger galaxies are also more metal rich. This relation is true even when the age and metallicity are measured in completely independent index–index diagrams, indicating that it is not a consequence of a correlation of the errors in both parameters. However, the actual relation can be flatter than the relation derived from a partially degenerate index–index diagram. We have shown that this relation is only evident when some indicators are used to measure the metallicity. In particular, we do not find a relation when the metallicity is measured in a Mgb–Hβ diagram. If the age–metallicity relation is a consequence of the occurrence of late star formation in these galaxies, this would imply that the relative enrichment in Mg in the last generations of stars is much less important with respect to the Fe. The sample of HDEGs, however, do not show this relation between the age and the metallicity, which is in agreement with the general picture exposed in this work (and in Paper I) in which HDEGs have had a truncated star formation history compared to their counterparts in low-density environments.

- There exists a mass–metallicity relation for HDEGs, in the sense that more massive galaxies tend to be also more metal rich. This is independent of the indicator used to measure the metallicity, although the slope is somewhat shallower if Fe4383 is used instead of Mgb or CN2. However, in the case of the LDEGs the mass–metallicity relation is only apparent when the metallicity is measured with Mgb. When the metallicity is measured with Fe4383 or CN2, younger galaxies tend to lie at higher metallicities for a given $\sigma$. This can indicate that the mass–metallicity relation is a consequence of processes that occurred when the bulk of the stars were formed. In LDEGs, later star formation events raise the metallicity in low-mass systems, flattening this relation. As the relative enrichment in these events is more pronounced in the elements produced by low-mass stars, the flattening in the relation, when the metallicity is measured with indices sensitive to these elements, is also more evident.

Our results show that there exist differences in the stellar populations of galaxies inhabiting different environments. HDEGs represent a more homogenous sample of galaxies than LDEGs, their stellar populations can be explained assuming a single burst and their mean ages are slightly higher. On the other hand, LDEGs show more variety in their stellar populations. They span a large range of ages and their spectral features are better explained assuming that they have suffered multiple bursts of star formation.

It is worth recalling that the results discussed in Papers I and II of this series refer only to the central regions of the galaxies. If significant radial age and metallicity gradients are present within the galaxies, these results cannot be considered representative of the whole star formation history. That is, to constrain the star formation history of early-type galaxies, we cannot ignore the behaviour of the SSP-parameters along the radii. This analysis is beyond the scope of the present paper, but will be the subject of the third paper of the series.

Acknowledgments

We are very grateful to the referee, Jim Rose, for his very constructive report and many useful suggestions. We are also grateful to Javier Cenarro, Reynier Peletier and Alexandre Vazdekis for many fruitful discussions. The WHT is operated on the island of La Palma by the Royal Greenwich Observatory at the Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias. The Calar Alto Observatory is operated jointly by the Max-Planck Institute für Astronomie, Heidelberg, and the Spanish Instituto de Astrofísica de Andalucía (CSIC). This work was supported by the Spanish research project AYA 2003-01840 and by the Australian Research Council. We are grateful the CAT for generous allocation of telescope time.

References

Baugh C.M., Cole S., Frenk C.S., 1996, MNRAS, 283, 1361
Bender R., Möllenhoff C., 1987, A&A, 177, 71
Bender R., Burstein D., Faber S.M., 1992, ApJ, 399, 462
Bender R., Burstein D., Faber S.M., 1993, ApJ, 411, 153
Bernardi M., Renzini A., da Costa L.N., Wegner G., Alonso M.V., Pelligrini P.S., Rité C., Willmer C.N.A., 1998, ApJ, 508, L143
Bressan A., Chiosi C., Tantalo R., 1996, A&A, 311, 425

P. Sánchez–Blázquez et al.: Stellar populations of early-type galaxies in different environments II 17
Worthey G., 1998, PASP, 110, 888
Worthey G., Ottaviani D.L., 1997, ApJS, 111, 377
Ziegler B.L., Bower R.G., Smail I., Davies R.L., Lee D., 2001, MNRAS, 325, 1571
This figure "figure11a.png" is available in "png" format from:

http://arxiv.org/ps/astro-ph/0604568v1
This figure "figure11b.png" is available in "png" format from:

http://arxiv.org/ps/astro-ph/0604568v1
This figure "figure11c.png" is available in "png" format from:

http://arxiv.org/ps/astro-ph/0604568v1
This figure "figure14a.png" is available in "png" format from:

http://arxiv.org/ps/astro-ph/0604568v1
This figure "figure14b.png" is available in "png" format from:

http://arxiv.org/ps/astro-ph/0604568v1