This is the third 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. We present line-strength gradients for 22 spectral indices measured in a sample of 82 early-type galaxies in different environments, including the high-density core of the Coma cluster, the Virgo cluster, poor groups, and isolated field galaxies. Using new evolutionary population synthesis models we derive age and metallicity gradients, and compare the mean values with the predictions of different galaxy formation models. We explore the behaviour of individual chemical species by deriving the metallicity gradient with different indicators. We find that the strength of the metallicity gradient inferred from stellar population models depends on the specific Lick index employed. In particular, metallicity gradients obtained with CN$_2$ and Ca4668 combined with H$\beta$ are steeper than when measured using Ca4227 or Fe4383. The correlation of the metallicity gradients with other parameters also depends on the specific index employed. If the metallicity gradient is obtained using CN$_2$ and Mgb then it correlates with the central age of the galaxies. On the contrary, if Fe4383 or Ca4227 are used, the metallicity gradient correlates with the velocity dispersion gradient. This may suggest that several mechanism have helped to set the age and metallicity gradients in early-type galaxies. While we do not find any correlation between the metallicity gradient and the central velocity dispersion for galaxies in low-density environments, we find a marginal correlation between the metallicity gradient and the mass for galaxies in the centre of the Coma cluster. We also find a trend for which galaxies in denser environments show a steeper metallicity gradient than galaxies in less dense environments. We interpret these results in light of the different mechanisms proposed to explain the observed changes between galaxies as a function of environment.

**Key words.** galaxies: abundances – galaxies: formation – galaxies: elliptical and lenticular – galaxies: evolution – galaxies: kinematics and dynamics
Stellar populations of early-type galaxies in different environments III

Line-strength gradients

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Abstract.

1. Introduction

This is the third paper in a series devoted to studying the properties of the stellar populations in early-type galaxies as a function of their local environment. In Sánchez-Blázquez et al. (2006a, hereafter Paper I) we presented central Lick/IDS index measurements for a sample of 98 early-type galaxies and described their relation to the velocity dispersion. In Sánchez-Blázquez et al. (2006b, hereafter Paper II) we compared the indices with the stellar population synthesis models of Vazdekis et al. (2006, in preparation; hereafter V06) to derive ages and metallicities. These models are an improved version of those described by Vazdekis et al. (2003) strengthened by the addition of a new stellar library (Sánchez-Blázquez et al. 2006, in preparation). The synthetic spectra cover a spectral range of λλ 3500 – 7500 Å at resolution 2.3 Å. The previous papers concentrated on the analysis of the central regions of the galaxies. In this paper we investigate the behaviour of these properties as a function of galactocentric radius.

It is well known that early-type galaxies show a variation of their stellar population properties with radius. The first evidence of this phenomenon was observed in the colours of bulges and elliptical galaxies (see the review by Kormendy & Djorgovski 1989) and indicated that the central regions tend to be redder than the outer parts. Other authors have measured optical surface brightness profiles for large sets of local ellipticals (e.g. Franx, Illingworth & Heckman 1989; Peletier et al. 1990), reaching the same conclusion. The first study of gradients in absorption features was performed by McClure (1969). In a sample of 7 galaxies, McClure found that the C(41 – 42) index (a measure of the CNλ 4216 band strength) was stronger in the centres of the galaxies than at a distance of 1 – 1.5 kpc, which he interpreted as a metallicity difference between the two regions. Subsequent work in the field has explored the strength of absorption feature gradients using a broad range of line indices (Spinrad et al. 1971; Spinrad, Smith & Taylor 1972; Welch & Forrester 1972; Joly & Andrillat 1973; Oke & Schwarzschild 1975; Cohen 1979; Efstathiou & Gorgas 1985; Couture & Hardy 1988; Peletier 1989; Thomsen & Baum 1989; Gorgas, Efstathiou & Aragón-Salamanca 1990; Boroson & Thompson 1991; Bender & Surma 1992; Davidge 1992; Davies, Sadler & Peletier 1993; Carollo, Danziger & Buson 1993; González 1993; Fisher, Franx & Illingworth 1995; Gorgas et al. 1997; Cardiel, Gorgas & Aragón-Salamanca 1998a; Mehlert et al. 2003). In general, these studies indicate the existence of intense gradients in CNλ 3883 and CNλ 4216, less pronounced gradients in the Mgλ 5176, G band, NaD, Ca H&K features, and in some lines of Fe i, and a weak or null gradient in Hβ, MgH, TiO, Ca i and in the calcium triplet in the near-infrared. Most of these studies have suggested that the existence of gradients in the metallic spectral features is a consequence of a decreasing metallicity with increasing galactocentric radius (e.g. Mc Clure 1969; Cohen 1979; Davies et al. 1993; Kobayashi & Arimoto 1999; Mehlert et al. 2003). Some, however, have argued that, apart from a variation of metallicity with radius, there is also a radial variation in the luminosity-weighted mean age of the stellar populations, with the central regions being younger than the outer regions (Gorgas et al. 1990; Munn 1992; González 1993; González & Gorgas 1996).

How the physical properties of galaxies vary with radius can prove invaluable for constraining the processes of galaxy formation and evolution. For example, metallicity gradients are a measure of the quantity, velocity, and duration of gas dissipation. Likewise, age and metallicity gradients contain informa-
tion concerning the relative importance of interactions during galaxy formation.

In the classical models of monolithic collapse (Eggen et al. 1962; Larson 1974a; Carlberg 1984; Arimoto & Yoshii 1987; Gibson 1997), stars form in essentially all regions during the collapse and remain in their orbits with little inward migration, whereas the gas dissipates inwards, being continuously enriched by the evolving stars. In this way, the stars formed at the centres of galaxies are predicted to be more metal-rich than those born in the outer regions. Supernova-driven galactic winds (Mathews & Baker 1971; Larson 1974b; Arimoto & Yoshii 1987; Gibson 1997), initiated when the energy injected into the interstellar medium (ISM) by supernovae matches that of its binding energy, act to evacuate the galaxy of gas, thereby eliminating the fuel necessary for star formation. The external parts of the galaxy (with a shallower potential well) develop winds before the central regions, where the star formation and, therefore, the chemical enrichment continue for longer. The monolithic collapse models, therefore, predict very steep metallicity gradients as both processes—the dissipation of gas toward the central parts of the galaxy and the different timescales for the occurrence of the galactic winds—act in the direction of steepening any nascent metallicity gradient.

Simulations of galaxy mergers within the concordant hierarchical clustering cold dark matter framework (e.g. Cole et al. 1994; Baugh, Cole & Frenk 1996; Kauffmann 1996; Kauffmann & Charlot 1998) offer somewhat contradictory predictions as to the radial variation of stellar properties in early-type galaxies—while some (e.g. White 1980; Bekki & Shioya 1999) suggest mergers lead of a flattening of metallicity gradients, others (e.g. van Albada 1982) argue that the gradients are affected only moderately by the mergers, as the violent relaxation preserves the position of the stars in the local potential. This apparent dichotomy between the simulations is driven in part by the sensitivity of the outcome to the fraction of gaseous versus stellar mass present in the progenitor galaxies. Broadly speaking, the predicted gradients are steeper if the progenitor galaxies have a large fraction of their pre-merger baryonic mass in the form of gas. Furthermore, numerical simulations suggest that during the merger a significant fraction of this gas migrates inward toward the central regions of the merging galaxies, resulting in increased central star formation (Barnes & Hernquist 1991). Mihos & Hernquist (1994) showed that the observed gradients in elliptical galaxies may be a consequence of the occurrence of secondary bursts of star formation triggered by these mergers.

One of the keys to demining the physical underlying the formation and evolution of galaxies is to study of the relations between the gradients and other fundamental (global) properties of galaxies. For instance, dissipational collapse models predict a strong positive correlation between metallicity gradient and galactic mass. The empirical evidence for such putative correlations remains contentious—e.g. Gorgas et al. (1990, G90 hereafter) did not find any relation between Mg$_2$ gradient and the rotation or total luminosity of a sample of early-type galaxies, although they found some evidence of a positive correlation between Mg$_2$ gradient and central velocity dispersion (a probability of 95% in a non-parametric Spearman test). Conversely, Franx & Illingworth (1990) found a correlation between colour gradient and local escape velocity (later confirmed by other authors, as Davies et al. 1993), arguing that the aforementioned galactic winds were the dominant mechanism controlling the metal content of early-type galaxies. Davidge (1992) analysed 12 bright ellipticals, searching for correlations between Mg$_2$ gradients and the central velocity dispersion ($\sigma_0$), the total luminosity, the shape of the isophotes, the fine structure parameter (Schweizer et al. 1990), and the anisotropy parameter ($\psi_0$), which defines the degree of rotation in a galaxy (Binney 1978). Davidge found weak correlations between the Mg$_2$ gradient and ($\psi_0$) and $\sigma_0$, and an absence of correlation with any of the other parameters. Carollo et al. (1993) carried out an exhaustive study of the gradients of several spectral features (Mg$_{1,2}$, NaD, TiO$_1$, TiO$_2$, and Fe5270) in a sample of 42 galaxies. Carollo et al. found a tendency for the slope of the gradients in the Mg$_2$ index to increase with the mass of the galaxy, but only for galaxies with masses below $10^{11}$ M$_\odot$. Carollo & Danziger (1994) studied the line-strength gradients in Mg$_2$ and (Fe) for five early-type galaxies, confirming the dependency between metallicity and local potential well depth as a function of galactocentric radius, albeit with significant scatter. González & Gorgas (1996) surveyed the Mg$_2$ gradient literature available at the time, discovering that galaxies with steeper Mg$_2$ gradients also possess stronger central Mg$_2$. They proposed a scenario in which star formation episodes in the centre of the galaxies are responsible for the correlation, pointing out that its existence implies that the global mass-metallicity relation is flatter than the mass-metallicity relation inferred from the central values. Recently, Mehlert et al. (2003) found a correlation between the gradients of some spectral features and the velocity dispersion gradient (which can be considered a measure of the potential well depth gradient). In contrast with González & Gorgas, Mehlert et al. did not find a correlation between the line-strength index gradients and the central values, or between the index gradients and the central velocity dispersion.

The results to date are, to some extent, contradictory and therefore incapable of providing unequivocal support to any particular galaxy formation scenario. This contradictory nature is driven, in part, by the requisite high signal-to-noise data and associated care in data reduction necessary to extract reliable gradients. Further, very few absorption features (mainly Mg$_1$) have been systematically explored with a suitably large sample of ellipticals. Our work has been designed specifically to address these shortcomings which have plagued the interpretation of the extant data, using a sample of 82 galaxies populating a range of local environmental conditions.

In Section 2, we describe the measurement of the line-strength gradients within our dataset. In Section 3, we compare these gradients with synthesis models to derive explicit age and metallicity gradients. Sections 4 to 7 analyse the stel-

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1 Galactic winds can produce metallicity gradients without invoking dissipation (e.g. Franx & Illingworth 1990; Martinelli, Matteucci & Colafrancesco 1998), with the local metallicity coupled directly to the local potential well depth and essentially independent of the galaxy formation collapse physics.
lar population gradients for a sample drawn from low density environments. In particular, Section 4 discusses the mean age and metallicity gradients, while in Section 5 we explore the existence of possible variations of the chemical abundance ratios with radius. In Section 6, we explore the existence of putative correlations between metallicity gradient and other galactic parameters. In Section 7, we use the stellar population global parameters, derived with the help of the gradients, to study whether the trends found in Papers I and II hold only for the central parts, or can be extended to the entire galaxy. Section 8 studies the mean gradients in the sample of galaxies drawn from the high-density core of the Coma cluster. Finally, in Section 9, we summarise our findings and conclusions.

2. Measurement of gradients

The parent sample from which galaxies are drawn consists of 98 early-type systems, of which 37 belong to the Coma cluster (high-density environment galaxies, hereafter HDEGs), while the rest are drawn from the field, small groups, and the Virgo cluster (low-density environment galaxies, hereafter LDEGs). Details of the sample, the observations, and associated data reduction, can be found in Paper I. From each fully reduced galaxy frame, a final frame was created by extracting spectra along the slit, binning in the spatial direction to guarantee a minimum signal-to-noise ratio per Å (S/N) of 20 in the spectral region of the Hβ index, ensuring a maximum relative error for this index (assuming a typical value of 1.5 Å) of 20% (see Cardiel et al. 1998b). Those galaxies which did not have a minimum of 4 spectra along the radius meeting this criterion were eliminated from the final sample, which left a total of 82 galaxies of sufficient quality to measure gradients – 21 HDEGs and 61 LDEGs.

An equivalent radius \( r(i) \) was assigned to each binned spectrum as

\[
\bar{r}(i) = \frac{\int_0^r \mu_i(r) dr}{\int_0^r \mu_i(r) dr},
\]

where

\[
\mu_i(r) = k 10^{b_i r}.
\]

The value of \( b_i \) for each spectrum was calculated by fitting the number of counts in each row of the detector (including all the rows in each spectrum plus the neighbours) to the relation

\[
\log N = b_i r + c,
\]

where \( N \) is the number of counts, \( r \) the radius in arcseconds, and \( c \) a constant. We projected the gradients over the major axis, multiplying the mean radius by a factor

\[
f = \sqrt{\cos^2 \theta + \left( \frac{a}{b} \right)^2 \sin^2 \theta},
\]

where \( \theta \) is the difference between the major axis and the position angle of the slit, and \( a \) and \( b \) represent the major and minor axis of the galaxy respectively. The \( a, b \) and \( \theta \) values for each galaxy can be found in Table 2 of Paper I.

Radial velocities and velocity dispersions were measured for each spectrum as a function of galactocentric radius as described in Paper I. The rotation curve and the velocity dispersion profile were used to measure the Lick/IDS indices at the resolution defined by this system, and to correct them for velocity broadening (again, as described in Paper I). Instead of using the individual values of the velocity dispersion for each spectrum measured at each radial “bin”, we fitted a smooth curve to the \( \sigma \) profile. This minimises the errors in the derived velocity dispersion, due to the lower signal-to-noise ratios in the external parts of the galaxies. Residual [OIII] emission profiles were also estimated as described in Paper I. These values were used to correct the Hβ index for emission using the relation derived by Trager et al. (2000a) – \( \Delta \text{H}β = 0.6 \) [OIII], where \( \Delta \text{H}β \) is the correction to the index, and [OIII] the equivalent width of the [OIII]λ5007 emission line. The Mg b and Fe5015 indices were also corrected from emission, as in the central spectra. The final kinematic, line-strength and emission profiles, together with their associated errors, are presented in Sánchez-Blázquez (2004).

We measured 19 Lick/IDS indices defined by Trager et al. (1998) for all the galaxies except for those observed in Run 3, for which only 15 indices could be measured. With the aim of reducing the random errors in the external parts of the galaxies, we have defined the following composite indices:

\[
\text{HA} = \frac{H_\alpha + H_\delta}{2},
\]

\[
\text{Balmer} = \frac{H_\alpha + H_\delta + H_\beta}{3}.
\]

To obtain the final values for the line strength indices we applied the same corrections as for the central indices (see Paper I). Finally, all indices were transformed into magnitudes, as described in Paper I.

Although the behaviour of the indices as a function of galactocentric radius is not perfectly linear for all 82 galaxies, with the aim of obtaining a quantitative measurement of their values, we performed a linear fit, weighted by the errors over all the indices, to the relation \( l' = c + d \log \frac{r}{r_e} \), where \( l' \) represents the index expressed in magnitudes, \( a_e \) is the effective radius projected over the major axis, i.e. \( a_e = r_{eff}/\sqrt{\pi} \) (\( r_{eff} \) being the effective radius), and \( d \) the index gradient, hereafter denoted by \( \text{grad} \). This projection can be done under the assumption that the contours of constant \( l' \) coincide with the isophotes, which has been confirmed by several earlier studies (e.g. Davies et al. 1993). To avoid the uncertainties and radial flattening due to seeing effects, the data within the central area corresponding to the seeing were excluded from the fit. The seeing was estimated directly from the observations on the 4 different runs. Fig. 1 shows some examples of the line-strength gradients for the galaxy NGC 2832.

In order to check the assumption of linearity for the gradients we have compared the central values derived in Paper I (integrated within an equivalent aperture of 4″ at redshift \( z = 0.016 \), i.e., ~1.3 kpc), with the expected values for this aperture inferred from the gradients. Fig. 2 shows this comparison for all the indices. Within each panel, the mean offset (\( \Delta \)) and the root mean square of the deviations (\( \sigma \)) are indicated. In general, the agreement is very good – the offsets are not statistically significant for any of the indices and the scatter is compatible with the errors, lending support to the adopted approximation of a linear fit.
Fig. 1. Variation of the indices CN$_2$, C4668 and H$\beta$ as a function of galactocentric radius for the galaxy NGC 2832. The upper axes show the radial distance from the centre of the galaxy in arcseconds. The solid line represents a linear fit to the data, as described in the text. The data within 0.9 of the galaxy’s centre were excluded from the fit to minimise the effects of seeing on the fitted gradients.

Fig. 2. Comparison of the Lick indices measured in the central spectra (integrated within an equivalent aperture of 4” at redshift $z = 0.016$ – i.e., $\sim 1.3$ kpc) and the indices obtained from the gradients integrating over the same aperture; $\sigma$ indicates the root mean square and $\Delta$ the mean offset between both measurements. The solid line indicates the 1:1 correspondence. In all cases, the mean offsets are not statistically significant.
3. Gradients in age and metallicity

Figure 3 shows the line-strength gradients in Fe4383, Mgb and Hβ, presented in index–index diagrams that combine both the central values and the line-strengths at one effective radius. Each central measurement (solid circle) is connected to its corresponding measurement in the outer region. Overplotted are the stellar population models of V06. As can be seen, most of the lines tend to be nearly parallel (although, admittedly, not entirely) to the iso-age lines taken from the theoretical grid, which indicates that the gradients are mostly due to variations in metallicity. However, there are several galaxies which show significant variations in both age and metallicity with radius. We return to this point towards the end of this Section.

To quantify this behaviour, we have transformed the line-strength gradients into age and metallicity gradients using the model predictions of V06, who make use of the code of Vazdekis (1999) updated with a new and improved stellar library (MILES, Sánchez-Blázquez et al. 2006; these models will be presented in the forthcoming paper V06).

With an aim to minimising the effects of low signal-to-noise data, we have designed a method that makes simultaneous use of 10 different indices. The selected indices are: H64, CN2, Ca4227, G4300, H44, Fe4383, Hβ, Fe5015, HA, and Balmer. We checked that the results did not depend on the particular choice of indices. None of the Mg indices were employed, as they could not be measured in all the galaxies from Run 3 due to the wavelength convergence of the spectra. In order to derive single estimates of age and metallicity gradients, we have followed a procedure which is divided into two steps: (i) obtaining individual errors for the age and metallicity gradients for all the galaxies in each index-index diagram, and (ii) deriving the final values of the age and metallicity gradients, along with their associated errors.

3.1. Obtaining the errors in the age and metallicity gradients

We first calculated the slopes of the constant age and metallicity lines in the models. The slopes of these lines change with the absolute values of age and metallicity but, in the region in which the galaxies are located, the values are almost constant. The derived slopes define a new diagram that we call “Δindex–Δindex” – in the associated Fig. 4, the dashed line represents the expected gradients in the indices if these were due, exclusively, to a variation in age (assuming a constant solar metallicity). On the other hand, the solid lines show the predicted gradients if the only parameter changing with radius was the metallicity (assuming a constant age of 10 Gyr). Fig. 4 also shows the gradients in Hβ and Fe4383 measured in the galaxy NGC 4842A. To derive the age and metallicity gradients, we project the position of the galaxy over the lines Δage=0 and Δ[M/H]=0, as shown by the dotted lines in the figure, and interpolate the projection over these lines.

For each galaxy, and in every Δindex–Δindex diagram, we performed 10⁴ Monte Carlo simulations in which each point was perturbed with our errors, following a Gaussian probability distribution. For each simulation, an age and metallicity gradient was obtained. This process was repeated with all possible paired combinations of indices. As an illustration, Fig. 5 shows the values of age and metallicity gradients derived for NGC 4842A, using the ΔHβ–ΔMgb and ΔMgb–ΔFe4383 diagrams. As can be seen, due to the non-orthogonality of the index-index diagrams, there is an artificial anti-correlation between the age and the metallicity gradients. To obtain the error in the age and metallicity gradient for each galaxy, in every diagram, we projected these ellipses over the x- and y-axes and calculated the standard deviation of the resultant Gaussian. We
Table 1. Velocity dispersion and line-strength gradients for the sample of 82 galaxies. A portion of the table is shown for guidance regarding its form and content. For each galaxy and index, the first line shows the measured gradient, while the second row lists its corresponding formal error. The full table is available in the electronic edition of this paper.

| Galaxy   | σ   | D4000 | Hβ_A | Hβ_F | CN2  | Ca4227 | G4300 | Hγ_A | Hγ_F | Fe4383 |
|----------|-----|-------|------|------|------|--------|-------|------|------|--------|
| NGC 221  | 0.0877 | -0.0520 | -0.0014 | 0.0008 | -0.0247 | -0.0110 | 0.0104 | 0.0018 | 0.0079 | 0.0025 |
| 0.0126   | 0.0058 | 0.0023 | 0.0026 | 0.0057 | 0.0035 | 0.0025 | 0.0020 | 0.0032 | 0.0017 |
| Ca4455   | 0.0027 | -0.0030 | -0.0037 | -0.0021 | 0.0052 | -0.0009 | 0.0092 | -0.0017 | -0.0038 | 0.0020 |
| Fe4531   | 0.0019 | 0.0016 | 0.0017 | 0.0016 | 0.0019 | 0.0011 | 0.0022 | 0.0018 | 0.0011 | 0.0017 |

Fig. 4. Variations in the Hβ and Fe4383 line-strength indices expected through changes in metallicity at a constant age of 10 Gyr (solid line), and by variations in the age at constant solar metallicity (dashed line). The point represents the values of the gradients for the galaxy NGC 4842A with their associated error bars. The dotted lines indicate the projections of the values over the lines of constant age and constant metallicity.

denote the typical errors by $\sigma_{\text{grad}[\text{age}]}$ and $\sigma_{\text{grad}[\text{M/H}]}$, where $i$ refers to each index–index diagram.

3.2. Obtaining the age and metallicity gradients

Once we have obtained the typical errors associated with the inferred age and metallicity gradients for each index–index combination, we again performed (for each galaxy) $10^4$ Monte Carlo simulations, into which Gaussian noise was added to each line-strength index. Simulations were performed for each index independently, as opposed to each index–index diagram (note that once an index value is simulated, its particular value is fed simultaneously to all the possible diagrams taking into account the fact that not all of the different diagrams are independent).

We then measured the age and metallicity gradients of all the values obtained in all the simulations $j$, using all the different diagrams $i$. The mean age and metallicity gradient of simulation $j$ was obtained as an average of the age and metallicity gradients obtained for this particular simulation using all the different diagrams $i$, namely

$$\text{grad}[\text{age}]_j = \frac{\sum_{i=1}^{n_{\text{com}}} \frac{\text{grad}[\text{age}]_{i,j}}{\sigma(\text{grad}[\text{age}])_i^2}}{\sum_{i=1}^{n_{\text{com}}} \frac{1}{\sigma(\text{grad}[\text{age}])_i^2}}.$$ 

Fig. 5. Age and metallicity gradients obtained for the $10^4$ Monte Carlo simulations performed in the diagrams $\Delta H\beta$–$\Delta$Mgb (top panel) and $\Delta$Mgb–$\Delta$Fe4383 (bottom panel) for NGC 4842A. The correlation of the errors is larger when the age and metallicity are inferred from the latter.
and
\[
\text{grad}[M/H]_j = \frac{\sum_{i=1}^{n_{\text{sim}}} \text{grad}[M/H]_{i,j}}{\sqrt{\frac{1}{n_{\text{sim}}}}} ,
\]
where \(\text{grad}[\text{age}]_j\) represents the age gradient obtained with the \(i^{th}\) diagram in the simulation \(j\), \(\sigma(\text{grad}[\text{age}])\), the uncertainty of the age gradient in \(i\)-th diagram (obtained in the first step of the process), \(\text{grad}[M/H]_{i,j}\) the metallicity gradient in simulation \(j\) (using the \(i^{th}\) diagram), and \(\sigma(\text{grad}[M/H])\), the error in the metallicity gradient in this diagram; \(n_{\text{com}}\) indicates the total number of diagrams, which is the number of possible index pairs \((n_{\text{com}}=45)\).

Finally, the age and metallicity gradients for each galaxy were calculated as the mean values of all the simulations, i.e.
\[
\text{grad}[\text{age}]_{\text{final}} = \frac{\sum_{j=1}^{n_{\text{sim}}} \text{grad}[\text{age}]_j}{n_{\text{sim}}} ,
\]
and
\[
\text{grad}[M/H]_{\text{final}} = \frac{\sum_{j=1}^{n_{\text{sim}}} \text{grad}[M/H]_j}{n_{\text{sim}}} ,
\]
being \(n_{\text{sim}}\) the number of simulations performed for each line-strength index gradient. The final errors in the age and metallicity gradients were obtained as the standard deviations of the values obtained for each simulation, that is
\[
\sigma(\text{age}) = \sqrt{\frac{\sum_{j=1}^{n_{\text{sim}}} (\text{grad}[\text{age}]_j - \text{grad}[\text{age}]_{\text{final}})^2}{n_{\text{sim}} - 1}} ,
\]
and
\[
\sigma(\text{M/H}) = \sqrt{\frac{\sum_{j=1}^{n_{\text{sim}}} (\text{grad}[M/H]_j - \text{grad}[M/H]_{\text{final}})^2}{n_{\text{sim}} - 1}} .
\]

This process was performed for all 82 galaxies in our sample. The final values for the age and metallicity gradients obtained in this way, together with the associated errors, are listed in Table 2.

Figure 6 shows three different \(\Delta\text{index}–\Delta\text{index}\) diagrams in which we have over-plotted the galaxies in low-density environments. The lines of constant age and metallicity divide these diagrams into four distinct regimes. These regimes indicate the position of the galaxies with positive/negative differences in age and metallicity between the central and the external parts, as labeled in the panels. As can be seen, most of the galaxies are situated in the regime consistent with their centres being younger and more metal-rich than their outer regions. The bulk of the galaxies, however, are further away from the line \(\Delta[M/H]=0\) (dashed line) than from the line \(\Delta\text{age}=0\) (solid line), suggesting that the gradients in the line-strength indices are due (mostly) to variations of metallicity with radius.

4. Mean gradients

The predicted mean values of the age and metallicity gradients are dependent upon the merging history of the galaxies. In general, dissipative processes tend to steepen the metallicity gradient while major mergers are expected to dilute it. In the simulations of Kobayashi (2004), the typical gradients for non-merger and merger galaxies are \(\Delta[\text{Fe}/\text{H}] / \Delta \log r \sim -0.45, -0.38, \Delta[\text{O}/\text{H}] / \Delta \log r \sim -0.25, -0.24, \Delta \log Z / \log r \sim -0.30, -0.24\), respectively. We now analyse the mean age and metallicity gradients for the sample of LDEGs. Table 3 lists these values, together with relevant associated statistics (see below).
Table 2. Age and metallicity gradients derived with the method of Sec. 3 (second and third columns), and metallicity gradients derived in several index–index diagrams using different metallicity indicators (as indicated in the column headers) combined with Hβ. The second row for each galaxy indicates the associated errors in the gradients.

| Galaxy  | grad(age) ±σ | grad([M/H]) ±σ | CN2 grad([M/H]) ±σ | C4668 grad([M/H]) ±σ | Fe4383 grad([M/H]) ±σ | Mgb grad([M/H]) ±σ | Ca4227 grad([M/H]) ±σ |
|---------|--------------|----------------|-------------------|----------------------|----------------------|-------------------|----------------------|
| NGC 221 | 0.0151       | −0.0273        | −0.170            | −0.246               | 0.023                | −0.171            | 0.082                |
| NGC 315 | 0.0180       | 0.0226         | 0.241             | 0.139                | 0.222                | 0.259             | 0.373                |
| NGC 507 | −0.6291      | 0.5756         | 0.076             | 0.451                | 1.004                | 0.453             | 0.935                |
| NGC 584 | 0.0814       | −0.1937        | −0.673            | −0.510               | −0.341               | −0.414            | −0.294               |
| NGC 636 | 0.0779       | −0.3627        | −0.740            | −0.804               | −0.427               | −0.291            | 0.117                |
| NGC 821 | 0.0563       | −0.8237        | −1.560            | −1.058               | −0.493               | −0.981            | −1.057               |
| NGC 1453| −0.2652      | −0.1014        | −0.170            | −0.246               | 0.023                | −0.171            | 0.082                |
| NGC 1600| 0.1036       | 0.1259         | 0.241             | 0.139                | 0.222                | 0.259             | 0.373                |
| NGC 1700| 0.2293       | −0.0732        | −0.765            | −0.521               | −0.592               | −0.561            | −0.897               |
| NGC 2300| 0.1116       | 0.1349         | 0.186             | 0.183                | 0.237                | 0.274             | 0.508                |
| NGC 2329| 0.1284       | 0.1582         | 0.270             | 0.156                | 0.252                | 0.353             | 0.508                |
| NGC 2693| 0.2413       | −0.3977        | −0.610            | −0.510               | −1.081               | 1.243             | −0.014               |
| NGC 2694| 0.1731       | 0.1840         | 0.346             | 0.284                | 0.377                | 0.884             | 0.478                |
| NGC 2778| −0.1917      | −0.0072        | −0.420            | −0.220               | 0.049                | 0.210             | −0.168               |
| NGC 2832| 0.0786       | 0.0997         | 0.116             | 0.138                | 0.206                | 0.205             | 0.265                |
| NGC 3115| −0.1551      | −0.0214        | 0.119             | −0.531               | 0.270                | 0.186             | −0.882               |
| NGC 3377| 0.2540       | 0.2572         | 1.146             | 0.218                | 0.467                | 0.853             | 1.057                |
|         | 0.0644       | −0.3501        | −1.041            | −0.733               | −0.284               | −1.158            | −0.233               |
|         | 0.0879       | 0.1155         | 0.186             | 0.125                | 0.178                | 0.182             | 0.249                |
|         | 0.1436       | −0.3521        | −0.819            | −0.747               | −0.712               | 4.801             | −1.200               |
|         | 0.0696       | 0.1046         | 0.120             | 0.102                | 0.196                | 1.205             | 0.297                |
|         | 0.2518       | −0.4864        | −1.121            | −0.691               | −0.416               | −0.692            | −0.367               |
|         | 0.0501       | 0.0845         | 0.154             | 0.070                | 0.090                | 0.103             | 0.129                |
|         | 0.0334       | −0.3600        | −1.118            | −0.960               | −0.498               | −1.143            | −0.229               |
|         | 0.0679       | 0.1147         | 0.152             | 0.103                | 0.241                | 0.214             | 0.222                |

4.1. Age gradients

The mean age gradient for the sample of LDEGs is Δlog(age)/Δlog r = 0.082 ± 0.015. A t-test indicates that the probability of this value being different from zero by chance is < 0.1%. The positive gradient indicates that, on average, the centres of the galaxies are younger (or at least, they contain a percentage of younger stars which make the mean luminosity-weighted age lower) than the outer parts. The existence of a significant age gradient is difficult to explain within monolithic collapse scenarios, as the timescales for star formation are necessarily very short, but it does suggest that secondary episodes of star formation have occurred recently in the centres of the galaxies.

Little work has been done to date on the derivation of age gradients within early-type galaxies. Indeed, most of the extant studies of gradients in the literature assume the absence of an age gradient in order to derive the metallicity gradient. Munn (1992) was the first author that studied, in a systematic way, the variation of age with the galactocentric radius. From a sample of seven early-type galaxies, Munn combined the CN13883 and CN14216 features with the D4000 index to compare with the prediction of stellar population models. Since the age calibration employed by Munn was necessarily restricted to the assumption of solar metallicity, his ability to quantify the inferred gradients was limited. He did however conclude that in order to explain the dispersion and trends in the CN–D4000 diagrams, a variation of at least two parameters with radius was necessary (as suggested already by G90), with age and metallicity being the obvious candidates. Using the stellar population models of Worthey (1994), González (1993) found a mean variation in the age of his sample of galaxies of ~20% from the centre to the effective radius (he also found a variation of ~50% in metallicity). Fisher, Franx & Illingworth (1996) found in their sample of lenticulars that the centres were slightly younger than the external parts, although they did not quantify the result. Contrary
to these results, Mehlert et al. (2003) found, in a sample of galaxies from the Coma cluster, a mean age gradient compatible with being null. The discrepancy between the above results and those of Mehlert et al. (2003) may be due to the different environments from which the samples were drawn. We analyse the gradients for the HDEGs in Sec. 4.2.

Table 2. Continued.

| Galaxy | grad(log age) | grad([M/H]) | CN$_2$ | C4668 | Fe4383 | Mgb | Ca4227 |
|--------|---------------|-------------|--------|-------|--------|------|--------|
|        | $\pm \sigma$  | $\pm \sigma$ | $\pm \sigma$ | $\pm \sigma$ | $\pm \sigma$ | $\pm \sigma$ | $\pm \sigma$ |
| NGC 3379 | 0.1055 | -0.2279 | -0.515 | -0.419 | -0.239 | -1.069 | -0.262 |
| NGC 3605 | 0.0347 | 0.0528 | 0.066 | 0.051 | 0.072 | 0.128 | 0.098 |
| NGC 3608 | 0.0574 | -0.3890 | -0.050 | -0.385 | -0.869 | -0.452 | 0.235 |
| NGC 3641 | 0.1046 | 0.1486 | 0.218 | 0.191 | 0.278 | 0.288 | 0.348 |
| NGC 3665 | 0.0595 | -0.3767 | -0.906 | -0.575 | -0.145 | -0.706 | 0.104 |
| NGC 3818 | 0.1043 | 0.1180 | 0.216 | 0.209 | 0.230 | 0.306 | 0.334 |
| NGC 4278 | 0.0067 | -0.3821 | -1.608 | -0.547 | -0.209 | -0.856 | -0.261 |
| NGC 4261 | 0.2529 | 0.2634 | 0.501 | 0.359 | 0.491 | 0.636 | 0.731 |
| NGC 4278 | 0.0616 | -0.1746 | -0.092 | -0.383 | -0.105 | -0.086 | 0.284 |
| NGC 4365 | 0.0716 | 0.0941 | 0.166 | 0.095 | 0.163 | 0.215 | 0.285 |
| NGC 4374 | 0.1865 | -0.3875 | -1.089 | -0.874 | -0.295 | -0.840 | -0.216 |
| NGC 4378 | 0.0728 | 0.1087 | 0.152 | 0.106 | 0.147 | 0.172 | 0.203 |
| NGC 4415 | 0.4048 | 0.0647 | 0.081 | 0.056 | 0.095 | 0.121 | 0.132 |
| NGC 4431 | 0.0378 | 0.0542 | 0.069 | 0.050 | 0.077 | 0.091 | 0.121 |
| NGC 4464 | -0.1112 | -0.0716 | -0.452 | -0.258 | -0.000 | -0.239 | 0.154 |
| NGC 4467 | 0.0421 | 0.0668 | 0.109 | 0.077 | 0.092 | 0.126 | 0.158 |
| NGC 4472 | 0.1048 | -0.0759 | 0.074 | -0.038 | -0.071 | -0.428 | -0.581 |
| NGC 4478 | 0.0625 | 0.0658 | 0.136 | 0.080 | 0.104 | 0.243 | 0.183 |
| NGC 4486B | 0.1725 | -0.1285 | -0.610 | -0.216 | -0.260 | -0.409 | -0.548 |
| NGC 4489 | 0.0928 | 0.1048 | 0.189 | 0.145 | 0.194 | 0.219 | 0.423 |
| NGC 4552 | -0.1041 | -0.0150 | -0.550 | -0.206 | -0.009 | -0.374 | 0.213 |
| NGC 4552 | 0.0796 | 0.0931 | 0.169 | 0.141 | 0.141 | 0.178 | 0.226 |
| NGC 4552 | 0.0916 | -0.5234 | -0.798 | -1.202 | -0.719 | -0.669 | -0.303 |
| NGC 4552 | 0.2661 | 0.2767 | 0.492 | 0.504 | 0.526 | 0.782 | 0.719 |
| NGC 4552 | 0.1062 | -0.3919 | -0.543 | -0.472 | -0.220 | -0.331 | -0.506 |
| NGC 4552 | 0.0252 | 0.0460 | 0.047 | 0.035 | 0.056 | 0.072 | 0.091 |
| NGC 4552 | 0.0508 | 0.0667 | 0.087 | 0.056 | 0.090 | 0.122 | 0.135 |
| NGC 4552 | 0.4092 | -0.3663 | -1.059 | -0.891 | -0.362 | -1.184 | -0.337 |
| NGC 4552 | 0.2165 | 0.2441 | 0.260 | 0.200 | 0.483 | 0.442 | 0.576 |
| NGC 4552 | 0.3077 | -0.4354 | -0.259 | -0.700 | -0.752 | -0.359 | -0.483 |
| NGC 4552 | 0.1042 | 0.1423 | 0.228 | 0.164 | 0.260 | 0.228 | 0.492 |
| NGC 4552 | 0.0526 | -0.2075 | -0.782 | -0.584 | -0.158 | -0.546 | -0.091 |
| NGC 4552 | 0.0674 | 0.0939 | 0.127 | 0.076 | 0.151 | 0.144 | 0.287 |

4.2. Metallicity gradients

The mean metallicity gradient in our sample of LDEGs is \( \Delta [M/H]/\log r = -0.206 \pm 0.019 \). Earlier studies have derived comparable gradients using, primarily (Fe) and Mg indices. For example, Couture & Hardy (1988), using the Mg$_2$ index, found a variation in metallicity with radius of \( \Delta [M/H]/\log r = -0.25 \). G90 measured mean gradients in their sample of early-type galaxies of \( \Delta [M/H]/\log r = -0.23 \pm 0.09 \) and \( \Delta [M/H]/\log r = -0.22 \pm 0.10 \), using the Mg$_2$ and (Fe) indices, respectively (later confirmed by Davies et al. 1993). To transform the line-strength gradients into metallicity gradients, each of these studies used the Mould (1978), Burstein (1979), and Faber et al. (1985) calibrations. In all cases, they assumed a null age gradient. Fisher et al. (1995), through the comparison of the gradients of Mg$_2$, H$_\beta$, and (Fe), with the stellar population models of Worthey (1994), obtained a metallicity gradient of \( \Delta [M/H]/\log r = \).
Finally, we compared the dispersion about the mean values ($\sigma = 0.151$) and the scatter expected from the errors ($\sigma_{\text{exp}}=0.075$) by performing a $\chi^2$ test. The hypothesis $\sigma_{\text{exp}} = \sigma$ can be rejected at a low significance level (see 8th column of Table 3). To investigate the causes of the variation in the metallicity gradients among galaxies, in Section 6 we explore putative correlations of the gradients with other physical galaxy parameters.

5. Relative radial abundance ratios

It is well known that massive early-type galaxies have abundance patterns that do not match that of the solar neighbourhood (see Paper II, and references therein). Although the influence of non-scaled solar abundance ratio patterns complicates the estimation of mean ages from integrated light, it does provide an important clue as to the formation and chemical en-

| Galaxy      | grad(age) | grad([M/H]) | CN_2 | C4668 | Fe4383 | Mgb | Ca4227 |
|-------------|-----------|-------------|------|-------|--------|-----|--------|
| NGC 4564    | 0.1010    | -0.3264     | -0.50 | -0.740| 0.050  | -0.520| -0.613 |
| NGC 4594    | 0.1078    | -0.3880     | -0.107| 0.079 | -0.594 | -0.162| -0.281 |
| NGC 4621    | 0.1645    | -0.4335     | -0.272| 0.142 | -0.435 | -0.353| 0.496  |
| NGC 4636    | 0.2275    | -0.3357     | -0.907| 0.067 | -0.335 | -0.594| -0.274 |
| NGC 4649    | 0.0766    | -0.0981     | 0.178 | 0.120 | 0.114  | 0.143 | 0.184  |
| NGC 4673    | -0.1593   | -0.1049     | -0.231| -0.540| 0.252  | -0.580| -0.415 |
| NGC 4692    | 0.0960    | 0.1239      | 0.176 | 0.175 | 0.213  | 0.249 | 0.339  |
| NGC 4697    | 0.4245    | -0.1537     | -0.706| -0.502| -0.131 | -0.403| -0.113 |
| NGC 4742    | 0.0248    | 0.0423      | 0.046 | 0.040 | 0.055  | 0.071 | 0.086  |
| NGC 4839    | 0.0804    | -0.6647     | -0.655| -0.771| -0.840 | -1.174| -1.053 |
| NGC 4842A   | -0.2147   | 0.0637      | -1.015| 0.098 | -0.324 | 1.459 | 1.735  |
| NGC 4864    | 0.2617    | 0.2364      | 0.721 | 0.295 | 0.619  | 0.676 | 0.709  |
| NGC 4865    | 0.4900    | -0.5792     | -0.479| -0.697| -1.175 | -0.998| -0.692 |
| NGC 4874    | 0.1232    | 0.1416      | 0.370 | 0.175 | 0.261  | 0.339 | 0.368  |
| NGC 4875    | 0.1029    | 0.1382      | 0.225 | 0.136 | 0.265  | 0.316 | 0.411  |
| NGC 4889    | 0.1777    | -0.3231     | -0.704| -0.869| -0.248 | -0.152| -0.582 |
| NGC 4908    | 0.1390    | 0.2141      | 0.852 | 0.588 | 1.212  | 1.398 | 1.876  |
| NGC 5638    | 0.2578    | -0.4363     | -0.793| -0.665| -0.534 | 0.052 | 0.136  |
| NGC 5796    | 0.1234    | -0.2664     | -0.340| -0.400| -0.120 | -0.608| -0.371 |
| NGC 5796    | 0.0744    | -0.0938     | 0.133 | 0.091 | 0.148  | 0.208 | 0.216  |
richment histories of galaxies. In this Section, we explore the presence of relative abundance ratios gradients in our sample of LDEGs. To do so, we compare the metallicity gradients obtained with different indices (combined with Hβ) and make the assumption that the differences in the derived values are due to the different sensitivity of the Lick indices to changes in the chemical composition. While avoiding a detailed quantitative analysis (due to the difficulty to perform this kind of analysis with the current stellar population models, see Paper II for details), the qualitative trends presented below do offer invaluable information concerning the formation of these galaxies and the timescales for star formation therein.

Fig. [I] shows three \( \Delta \text{index} - \Delta \text{index} \) diagrams in which gradients of \( \text{CN}_2 \), Mgb and \( \text{C}_4668 \) are compared against the gradients of Fe4383. The lines corresponding to \( \Delta \text{age}=0 \) and \( \Delta [\text{M}/\text{H}]=0 \) are over-plotted. Due to the low sensitivity to age of all these indices, the diagrams appear highly degenerate – i.e., the iso-age and iso-metallicity lines are almost parallel. If the galaxies did not have a gradient in the relative abundances, we would expect to find all the points distributed along these lines. However, they appear to be systematically shifted toward the left of the diagram, although the magnitude of these shifts is very different in the three plots. In the first panel (\( \Delta \text{Mgb} - \Delta \text{Fe}4383 \)), the metallicity gradients measured with Mgb are slightly steeper than the metallicity gradients inferred from Fe4383, although the differences are admittedly small. In the second panel (\( \Delta \text{CN}_2 - \Delta \text{Fe}4383 \)) the differences are more evident. The metallicity gradients obtained with \( \text{CN}_2 \) are clearly steeper (in absolute value) than the ones inferred from Fe4383. The last panel (\( \Delta \text{C}_4668 - \Delta \text{Fe}4383 \)) is an intermediate case between the first two. The metallicity gradient obtained with \( \text{C}_4668 \) is slightly steeper than the one estimated from Fe4383. Although the trend is not as evident as in the second panel, the points are visibly shifted toward the left of the constant age and metallicity lines.

To analyse these differences in more detail, we calculated the metallicity gradients in several index–index diagrams using the indices \( \text{CN}_2 \), \( \text{C}_4668 \), \( \text{Fe}4383 \), Mgb and \( \text{Ca}4227 \), combined with Hβ. In Fig. [IX] we compare these gradients with the values obtained from ten different indicators, as described in Sec. [IX].
Clearly, while the values obtained with Ca4227 and Fe4383 are compatible with the gradients obtained in Sec. 3, the gradients calculated with CN₂, C4668 and, perhaps, Mgb are steeper. We quantified this difference by measuring the mean gradient using the various diagrams, the results of which are summarised in Table 2. The final column of the table shows the probability that the mean gradients calculated with the various indicators are the same as the gradients calculated Section 3. The gradients calculated using CN₂ and C4668 are almost twice as steep as the gradients calculated with the average of ten indicators. In the case of Mgb, despite the mean gradient being almost twice as large steep as the mean metallicity gradient, the result is less significant. In that case, the initial hypothesis can be rejected with a significance level lower than 0.025.

We could argue that the differences in the metallicities derived with different indicators are due to variations in the chemical composition as a function of galactocentric distance, as the sensitivity of different Lick indices to variations on the abundance of different chemical elements is not the same (Tripicco & Bell 1995; Korn et al. 2004). But the Lick indices show a dependence with gravity that, while not large (Gorgas et al. 1993; Worthey et al. 1994), is also not null. As the behaviour of each line index under variations in the underlying IMF is not identical, a change in the ratio of dwarf-to-giant stars with galactocentric radius could result in the metallicity gradient inferred from different indicators also being different.

Cenarro et al. (2003) calibrated the CaT* (calcium triplet) index in the near-infrared and found a relationship between [Fe/H], velocity dispersion, and the slope of the IMF. One of the projections of this relationship is

$$\mu = 2.41 + 2.78[M/H] - 3.79[M/H]^2,$$

where \(\mu\) represents the slope of the IMF. Using this equation we determined the slope of the IMF from the average metallicities in the centre, and at a distance of one effective radius, finding the following values:

- \(\mu = 2.56\) in the central regions,

Table 2. Continued.

| Galaxy | grad(age) | grad([M/H]) | CN₂ | C4668 | Fe4383 | Mgb | Ca4227 |
|--------|-----------|-------------|-----|-------|--------|-----|--------|
| IC 3957 | 0.2298 ± 0.4788 | -0.890 ± 0.940 | -0.202 ± 0.082 | -2.087 |
| IC 3959 | 0.2385 ± 0.2636 | 0.769 ± 0.287 | 0.507 ± 1.048 | 0.612 |
| IC 3963 | 0.0731 ± 0.1642 | -1.038 ± 0.077 | 0.091 ± 0.545 | -0.565 |
| IC 3973 | 0.1344 ± 0.1655 | 0.214 ± 0.260 | 0.349 ± 0.316 | 0.510 |
| IC 3973 | 0.3360 ± 0.5703 | -0.424 ± 0.864 | -0.550 ± 0.765 | -1.322 |
| IC 3973 | 0.1340 ± 0.1788 | 0.300 ± 0.217 | 0.387 ± 0.436 | 0.595 |
| IC 4042 | 0.4122 ± 0.3849 | -0.692 ± 0.435 | -0.532 ± 1.091 | -0.595 |
| IC 4051 | 0.1776 ± 0.1643 | 0.374 ± 0.285 | 0.483 ± 0.735 | 0.820 |
| CGCG 159-41 | 0.4661 ± 0.6512 | 0.374 ± 0.285 | 0.483 ± 0.735 | 0.820 |
| CGCG 159-43 | 0.5742 ± 0.6968 | 1.401 ± 1.034 | 1.372 ± 1.443 | 1.416 |
| CGCG 159-83 | 0.5593 ± 0.6726 | -0.902 ± 0.751 | -0.480 ± 1.305 | -0.820 |
| CGCG 159-89 | 0.1641 ± 0.1936 | 0.281 ± 0.355 | 0.385 ± 0.386 | 0.618 |
| CGCG 159-89 | 0.1410 ± 0.1969 | 0.229 ± 0.134 | 0.351 ± 0.484 | 0.513 |

Table 3. Mean gradients of age, [M/H], and metallicity, derived with different indices for LDEGs. \(\sigma\): typical deviation; \(N\): number of galaxies; \(N_{\text{eff}}\): effective number of points, \(N_{\text{eff}} = \frac{\sum (1/\sigma^2)^2}{\sum (1/\sigma^2)}\); \(t\)-statistic to check the hypothesis “mean\(\neq 0\)”;

- \(\sigma_{\text{exp}}\): typical deviation expected from errors; \(\alpha\): level of significance to reject the hypothesis “\(\sigma = \sigma_{\text{exp}}\)”. The last column contains the \(t\)-statistic used to test the hypothesis “mean \([M/H] = \text{mean grad}[M/H]\)” (with different indices).

- \(\sigma_{\text{exp}}\): typical deviation expected from errors; \(\alpha\): level of significance to reject the hypothesis “\(\sigma = \sigma_{\text{exp}}\)”. The last column contains the \(t\)-statistic used to test the hypothesis “mean \([M/H] = \text{mean grad}[M/H]\)” (with different indices).
Fig. 7. $\Delta$index–$\Delta$index diagrams in which we compare the Fe4383 gradients with the gradients of Mg$b$, CN$_2$ and C4668. Dashed lines indicate the expected gradients if the only parameter varying with radius is the age (assuming an invariant solar metallicity), while solid lines show the expected trends if the only parameter changing with radius is the metallicity (assuming a constant age of 10 Gyr).

Fig. 8. Comparison of the metallicity gradient measured with different indicators combined with H$\beta$, and the metallicity gradient calculated combining ten different indicators (see text for details).

$\mu = 1.67$ at a distance of one effective radius from the galaxy centre.

To investigate the variation in the line-strength indices that such a variation in the IMF, plus an average variation in metallicity as obtained in Section 4 would produce, we parameterized the indices (using the V06 models) as a function of metallicity and $\mu$, obtaining:

CN$_2: 0.0374 - 0.0063\mu + 0.1350[M/H] + 0.0495[M/H]^2$
Ca4227: 0.3745 + 0.1600$\mu + 0.9547[M/H] + 0.1566[M/H]^2$
Fe4383: 0.5963 + 0.0467$\mu + 4.2390[M/H] + 0.8785[M/H]^2$
C4668: 0.5930 - 0.2943$\mu + 6.4247[M/H] + 1.8047[M/H]^2$

Mg$b: 0.7700 + 0.1303\mu + 2.2567[M/H] + 2.2567[M/H]^2$

A variation in the slope of the IMF, together with a variation in metallicity equal to the mean metallicity gradient calculated in Section 4 would produce the following differences in the selected indices: $\Delta$CN$_2 = 0.0278$ mag, $\Delta$Ca4227= 0.0390 mag, $\Delta$Fe4383= 0.0264 mag, $\Delta$C4668= 0.0182 mag, and $\Delta$Mgb= 0.0270 mag. The mean observed variations for the LDEGs are: $\Delta$CN$_{2obs} = -0.0662 \pm 0.0096$ mag, $\Delta$Ca4227$_{obs} = -0.0157 \pm 0.0097$ mag, $\Delta$Fe4383$_{obs} = -0.0174 \pm 0.0064$ mag, $\Delta$C4668$_{obs} = -0.0314 \pm 0.0044$ mag, and $\Delta$Mgb$_{obs} = -0.0301 \pm 0.0062$ mag. As can be seen, a variation of the IMF
of the form predicted by Cenarro et al. (2003) cannot be responsible for the different metallicity gradients obtained with the various indicators. In fact, this variation of the IMF would produce positive gradients in the selected indices. In this parameterisation we have not included the effect of age, but the age gradients are not very strong in our sample (see Section 6.1) and the differences in the sensitivities of the analysed indices to this parameter are not enough to produce the observed differences.

More likely, the differences in the metallicity gradients obtained with the different indices are due to changes in the relative abundance gradients of distinct elements. However, it is difficult to quantify the strength of those gradients with the present knowledge of line formation and the inherent limitations of stellar population synthesis models.

6. Correlation of the gradients with other parameters

There are several physical processes that can produce a metallicity gradient in early-type galaxies. The relationship between these gradients and other global properties of the galaxies afford an opportunity to discriminate between the competing processes. Previous attempts have searched for correlations using colours and empirical line-strength indices; in what follows, we study the correlation between the derived simple stellar population (SSP) parameters and the global properties of the host galaxies. In this section, we only use the subsample of elliptical galaxies, excluding the lenticulars (S0) from the analysis. The reason for doing this is that the correlations between the gradients and other parameters are predicted by an specific mechanism of galaxy formation, and, although S0 and E galaxies seem to follow the same relations between the central properties and other parameters, very different mechanisms have been proposed for their formation. As the sample of S0 is small, we could not perform a comparative study using only S0 galaxies.

6.1. Correlation of the metallicity gradient with the velocity dispersion gradient

As noted in Section 1, Franx & Illingworth (1990) found a correlation between colour gradient and the gradient of escape velocity, which they interpreted as a correlation between the local metallicity and the local potential well depth in a sample of early-type galaxies. They suggested that such a correlation was consistent with a galactic wind origin, and inconsistent with a dissipative inward flow origin. Others, including Davies et al. (1993), Carollo & Danziger (1994), and Mehlert et al. (2003) find similar relations between the gradients of some line-strength indices and the gradient of the potential well.

We now examine the likelihood for the existence of this correlation within our sample of LDEGs, using the inferred metallicity gradients and empirical velocity dispersion gradients – Fig. 9 illustrates the observed trends.

To study the degree of correlation we have performed two different tests: a non-parametric Spearman rank order test and a t-test. The Spearman test does not take into account the errors in the individual points, while the t-test has the limitation of considering just a linear relation and it assumes Gaussian probability distributions. A good estimate of the degree of correlation between both magnitudes can be obtained by studying the results of both tests. In the t-test, we check the hypothesis “b = 0”, where b is the slope of the linear fit to the data. The errors in the slope were calculated through Monte Carlo simulations, where each point was perturbed in both axes assuming a Gaussian distribution with standard deviation equal to the errors. For a significance level of α = 0.05, a t value higher than 1.96 indicates that a correlation exists. The results of both tests are shown in Table 4. In the second row of the table (and left top panel in Fig. 9) we show the correlation when the metallicity is measured with the ten indicators described in Sec. 4. We do not find any correlation between the metallicity gradients and the gradient of velocity dispersion. The other panels in the figure show the metallicity gradients obtained in different Δindex–Δindex diagrams in which we combined Hβ with various metallicity indicators (as indicated between the brackets). Surprisingly, we find a marginally significant correlation between the metallicity gradients and grad σ when the metallicity gradient is measured using Mgb and CN2 indices, while we do not find any correlation when the metallicity gradient is obtained using the other indices. If the correlation between these parameters is indicative of the importance of galactic winds during the evolution of early-type galaxies, the fact that the correlation only exists when the metallicity gradient is calculated with some specific indices may indicate that this process affects some chemical species more than others. This could happen if, for example, the relative abundance patterns were different when the galactic winds occurred.

The dispersion in the relations is, in any case, very large. This large scatter may be a consequence of using the velocity dispersion as an indicator of the local potential and/or indicative that other processes are driving the variation of the local metal content with radius. Davies et al. (1993), in fact, suggest that the local velocity dispersion is a poor indicator of the local escape velocity, due to the (complicating) presence of rotation and anisotropies. On the other hand, the existence of kinematically decoupled cores in a large percentage of galaxies, the presence of shells, dust lanes, and the observation of interacting galaxies, seem to indicate that mergers and interactions are common processes in the lives of galaxies. If these interactions have some associated gas dissipation and/or star formation, it may produce dispersion in the correlation between local metallicity and local escape velocity. In fact, other authors (Davies et al. 1993; Carollo & Danziger 1994) have found correlations between the Mgb and the velocity dispersion gradients using the...
local escape velocity instead of the velocity dispersion, finding also a large scatter in the relations.

We conclude that the local potential of early-type galaxies may play a role in defining the metallicity gradient. However, the large scatter in the derived correlation suggests that other processes may play a role in modulating the final metal content. These processes can be the consequence of differences in the merger histories of galaxies as proposed by Kobayashi (2004). The fact that the inferred metallicity gradients differ depending upon the indicator adopted also suggests that the gradients of the various chemical species have probably been formed (and modified) through different physical mechanisms.

6.2. Correlation of the metallicity gradient with the central velocity dispersion

Dissipative collapse models of galaxy formation predict strong correlations between the metallicity gradients and certain global parameters, such as the luminosity, mass, and central velocity dispersion (Larson 1974a; Carlberg 1984; Arimoto & Yoshii 1987; Kawata 1999; Chiosi & Carraro 2002; Kawata & Gibson 2003), in the sense that more massive galaxies should possess steeper metallicity gradients. Such a prediction is driven primarily by the adopted mass-dependent feedback efficiency within the models. Conversely, galaxy formation through hierarchical clustering of small sub-units does not necessarily lead to a clear prediction for any putative correlations between metallicity gradients and global galactic properties – merger history can readily play a part in eroding any extant correlation (e.g. Kobayashi 2004).

With the aim of exploring the possible correlation between metallicity gradient and galactic mass, we compare in Fig. 10 the metallicity gradients (obtained as described in Sec. 3) with the central velocity dispersion for the sample of LDEGs. The other panels in the figure show the relation between the metallicity gradient and the central velocity dispersion when the metallicity gradient is measured using CN$_2$, C4668, Fe4383, Mg and Ca4227 combined with H$_\beta$.

As in Section 6.1, we studied the degree of correlation through a $t$-test and a non-parametric Spearman test. The results of these tests are shown in Table 5. We did not find any correlation between the metallicity gradients and the central ve-
Fig. 10. Metallicity gradients obtained in different index–index diagrams (as indicated in brackets) versus the central velocity dispersion.

Table 5. Correlation between the gradients of age and metallicity and the central velocity dispersion. The brackets show the different indicators used to calculate the metallicity gradients. The first and the second rows refer to the values calculated using the ten indicators described in Section 3.

|                | N  | t     | Pnc |
|----------------|----|-------|-----|
| grad age       | 54 | -1.736| 0.168|
| grad [M/H]     | 54 | 0.810 | 0.106|
| grad [M/H] (CN₂–Hβ) | 54 | 1.075 | 0.789|
| grad [M/H] (Ca4227–Hβ) | 54 | 0.251 | 0.986|
| grad [M/H] (Fe4383–Hβ) | 54 | 1.303 | 0.244|
| grad [M/H] (Ca4227–Hβ) | 54 | 0.026 | 0.455|
| grad [M/H] (Mgb–Hβ) | 54 | 0.578 | 0.934|

6.3. Correlation of the gradients with the age of the central regions

In Section 6.1 we showed that, for the sample of LDEGs, the metallicity gradients tend to correlate with the velocity dispersion gradient when they are measured with some indicators (in particular CN₂ and Mgb) but that this correlation disappears when the metallicity gradient is measured with Fe4383, Ca4227, and C4668.

In Section 4 we showed that the mean age gradient in our sample of LDEGs is not null, which might be indicative of the occurrence of star formation events in the centre of the galaxies. Furthermore, we showed in Paper II than in these events, the relative enrichment of some chemical species (the ones mainly released by low- and intermediate-mass stars, like Fe) might be more important than others (the ones mainly produced in Type II supernovae, like Mg). With the aim of exploring the occurrence of star formation processes in the centre of the galaxies may be responsible for the abundance gradients in some chemical species, we now study the correlation between the metallicity gradients and the central ages obtained in Paper II. Fig. 11 shows these correlations for different measurements of the metallicity gradient. When the correlation is statistically significant, a linear fit taking into account the errors in the x- and y-directions is also plotted. In these cases, the probability of no correlation (Pnc) obtained in a non-parametric Spearman test, and the t parameter to verify the hypothesis b = 0 (where b is the slope of the linear fit), are indicated in the panels. As can be seen in the different panels, while we do not find any significant correlation when the metallicity gradients are measured with CN₂, Mgb, or Ca4227, we do find a correlation between the metallicity gradients and the central age of the galaxies when the former is measured using Fe4383 and C4668. We also find a significant correlation between the metallicity gradient obtained with the ten indicators described.
in Section 6.3 and the central age of the galaxies. We interpret these correlations in Section 6.4.

6.4. Interpretation of the Correlations for the LDEGs

In the Sections 6.1-6.3, we studied the putative correlations between metallicity gradient and other global properties of LDEGs. Broadly speaking, we found two distinct characteristics of the gradients depending upon the specific indicator used to derive them:

- **Metallicity gradients measured with CN2 and Mgb.** These correlate with the velocity dispersion gradient but they do not correlate with the central velocity dispersion or with the central age of the galaxies. This behaviour may indicate that the gradients of some elements (in particular Mg and N) are the result of processes such as galactic winds which can develop after an intense burst of star formation in the earliest phases of galaxy formation. The possible subsequent star formation in the galaxies has not modified substantially the variation of these elements with radius. This is in agreement with the results of Papers I and II where we argued that the relative enrichment of Fe in the star formation processes which occurred in the centre of the galaxies had to be more important than that of Mg.

- **Metallicity gradients measured with Fe4383 and C4668.** These gradients do not correlate with the velocity dispersion gradient but they do correlate with the central age of the galaxy. The correlation with the central age may indicate that episodes of star formation in the centre of the galaxies affects considerably the metallicity gradient for these chemical species, increasing the central metallicity.

This view agrees with the results of Papers I and II. Note that in galaxies that have suffered star formation episodes in their centres, the [Mg/Fe] gradient flattens as a consequence of the Fe enrichment in the central parts, which is supported by the relation between [Mg/Fe] and age reported in Paper I. This is also in agreement with the result presented in Paper II in which we found the existence of an age–metallicity relation when the metallicity was measured with Fe4383, but not when this parameter was measured with Mgb.

Conversely, in Sánchez-Blázquez et al. (2003) we reported differences in the N abundance between galaxies in different environments. If the star formation processes in the centres of the galaxies do not affect substantially the gradients in this element, then the differences must be visible not only in the centres, but in the outer parts.

We also note the behaviour of the metallicity gradient when inferred from Ca4227. Specifically, the gradient does not correlate with any of the obvious physical parameters – i.e., neither with the central age nor with the velocity dispersion gradient.

7. Global stellar population parameters

Many of the results described in Papers I and II could be explained by assuming the presence of a small percentage of young stars in the centre of most of the galaxies, at least in the subsample of LDEGs. We have also argued that this could be the cause of the existence of non-null age gradients in our sample of galaxies (see Sec. 4). If this point of view is correct, we would expect that the relations defined between the global parameters of the galaxies (i.e. for the whole bodies of the galaxies) are different than the one derived for the central
regions. To investigate this possibility, we now compare for the subsample of LDEGs the relation of these global values and the velocity dispersion with the relations derived for the central values in Paper II. The *global values* can be obtained from the gradients, assuming a linear behaviour of the indices with radius and evaluating the integral

\[ I_{\text{global}} = \frac{\int_0^\infty I(r) 2\pi I_c \exp^{-7.67[(r/r_e)^{1/4}-1]} \, dr}{\int_0^\infty 2\pi I_c \exp^{-7.67[(r/r_e)^{1/4}-1]} \, dr}, \tag{13} \]

where \( I(r) = a + b \log(r/r_e) \) represents the index at a distance \( r \) from the galaxy as derived from the gradient, and \( r_e \) is the effective radius. To solve this integral, we have assumed that the spatial profile of the galaxies can be approximated with a de Vaucouleurs law.

Fig. 12 shows the relation between the global age and global metallicities (as derived from different indicators) and the central velocity dispersion. The solid line indicates a linear fit to the data weighted with the errors in both parameters. In order to compare with the relations for the central regions, we have also plotted the linear fits obtained for the central values derived in Paper II (dashed lines). Table 6 summarises the parameters of the fits. We carried out a \( t \)-test to verify the existence of significant differences between the slopes of the trends defined by the central and the global SSP-parameters. A value of \( t \) higher than 1.96 indicates that there exist differences with a significance level lower than 0.05.

The only case in which the slopes defined by the central and the global values are significantly different is in the relation between the age and the central velocity dispersion. While the central age shows a significant correlation with the central velocity dispersion (see Paper II), the global age as derived in this section does not correlate with this parameter. This result favours the idea that the young ages that we found in Paper II in a large percentage of galaxies are due to a minor percentage of stars formed in the centre of the galaxies at a later epoch than the bulk of the stars, as suggested by Trager et al. (2000b). It also supports the suggestion that this minor percentage of young stars in the centre of the galaxies is responsible for the age gradients reported in Section 4.

On the other hand, the slopes of the relations between the metallicity and the central velocity dispersion do not show a statistically significant variation between the central and the global values, although there is a tendency for the relations to be steeper for the global values. There are also differences in the zero point as a consequence of the existence of gradients, in disagreement with the earlier claims of González & Gorgas (1996). These authors found that the relation \( \text{Mg}_2 - \sigma \) is flatter at one effective radii than in the center, concluding that the mass-metallicity relation was much flatter at one effective radii than in the central parts of the galaxies. In light of our present series of papers, the results of González & Gorgas could be explained if the differences between the central and global relation of the age with \( \sigma \) was causing these differences.

The lack of variation in the slope of the relation between the central and the global metallicities measured with CN\(_2\) and Mgb was expected, since we find a flat relation between the strength of the gradients and the central velocity dispersion. In the case of the metallicity measured with Fe4383 we might have expected to see a steepening of the slope in the global relation compared with the central one. If the relative importance of the star formation processes has been higher in the smaller galaxies (as suggested by the age–\( \sigma \) relation), the metallicity inferred from Fe4383 in these galaxies should be also higher. The variation in the slope obtained when comparing the central and the global relations goes in this sense, but the differences are not statistically significant. We must note that the errors in the global measurements are higher than for the central values, which might explain the lack of statistical significance.

8. Differences in the gradients as a function of environment

If the environment in which galaxies reside has any influence over the timescales of the star formation, the number of interactions, or the dissipation of gas, we might expect to see an environmental dependence upon the inferred age and metallicity gradients. Fisher et al. (1995) analysed a sample of bright
Table 6. Parameters of the linear fits, weighted with errors, of the age and metallicities (measured in different index–index diagrams indicated between brackets) and the central velocity dispersion. The table shows the results for the central values ($a_c$ and $b_c$) and for the global values ($a_g$ and $b_g$). The coefficients $a$ and $b$ represent the zero point and the slope of the linear fit, respectively. The last column shows the $t$ parameter obtained in a $t$-test to check the hypothesis $b_c = b_g$. A value of $t$ higher than 2.326 allows us to reject the hypothesis with a significance level lower than 0.01.

|        | central | global |
|--------|---------|--------|
| [M/H] (CN$_2$–H$b$) | $a_c$ | $b_c$ | $a_g$ | $b_g$ | $t$ |
|        | 0.335 ± 0.081 | 0.00037 ± 0.00034 | −0.012 ± 0.091 | 0.00080 ± 0.00038 | 0.86 |
| [M/H] (Fe4383–H$b$) | 0.148 ± 0.064 | −0.00050 ± 0.00030 | −0.275 ± 0.226 | 0.00041 ± 0.00087 | 0.98 |
| [M/H] (Mgb–H$b$) | 0.113 ± 0.075 | 0.00112 ± 0.00031 | −0.427 ± 0.286 | 0.00212 ± 0.00107 | 0.88 |
| log age | 9.534 ± 0.075 | 0.00177 ± 0.00033 | 9.950 ± 0.115 | 0.00007 ± 0.00049 | 2.88 |

cluster ellipticals, concluding that their gradients and those of field ellipticals, were not significantly different. Tamura & Otha (2003) found, studying the photometry in the B and R bands as a function of radius for galaxies in Abell 2199, correlations between the colour gradients and some global properties of the galaxies, such as the luminosity and effective radius, which had not been found in studies of field galaxies. These authors, however, only found these correlations amongst the most luminous galaxies ($R < 15$ mag and with an effective radius $>3\arcsec$). We now examine the mean gradients of the SSP-parameters for the HDEGs and compare these values with the ones obtained for the LDEGs.

8.1. Mean stellar population gradients in HDEGs

The second column of Table 7 lists the mean values of the SSP-parameter gradients obtained for the HDEGs in different index–index diagrams (indicated between brackets). As in Section 4, we quantified the probability that these values are different from zero by chance. The results of a $t$-test indicate that, while the metallicity gradients obtained in the CN$_2$–H$b$ and C4668–H$b$ diagrams are not compatible with being null, the metallicity gradients obtained in the Fe4383–H$b$ and Ca4227–H$b$ diagrams are compatible with zero, within the errors. Furthermore, the mean age gradient for this subsample of galaxies is also compatible with zero. We now analyse these results separately:

- **Age gradient.** If we assume that the most likely scenario to explain the age gradient in early-type galaxies is the occurrence of star formation processes in the centres of these systems, the lack of a mean age gradient in the HDEGs indicates that these galaxies have undergone few episodes of star formation in recent times, when compared with field galaxies. If the star formation processes are triggered by the interactions between galaxies, the differences could be explained due to the lower probability of an interaction in the centre of the Coma cluster. This is in agreement with the conclusions of Papers I and II, where we showed that the central stellar populations of the Coma cluster galaxies posed, on average, older ages than the LDEGs.

- **Metallicity gradients.** The mean metallicity gradient obtained for this subsample of galaxies is $\Delta\log\,[M/H]/\log r = −0.328 \pm 0.064$, slightly steeper than the gradient obtained for the LDEGs. From her simulations, Kobayashi (2004) predicts a metallicity gradient for galaxies that have not suffered major mergers of $\Delta\log Z/\Delta\log r \sim −0.3$. These predictions are in agreement with the mean values obtained for the galaxies in the Coma cluster. On the other hand, as for the LDEGs, the metallicity gradients are steeper when obtained with some indicators (CN$_2$, C4668 and Mgb), although the statistical significance of the differences is much lower than in the case of the LDEGs (see final column of Table 7). This may also be due to the larger errors in the determination of the gradients for the galaxies in the Coma cluster.

We have next checked to see if the scatter amongst the mean values was compatible with the dispersion expected by the errors. We carried out a $\chi^2$ test of the hypothesis $\sigma = \sigma_{exp}$ (where $\sigma$ is the observed scatter and $\sigma_{exp}$ the scatter expected from the errors), to see whether it could be rejected with a low significance level ($\Delta\sigma$). Column 8 of Table 7 shows the $\Delta\sigma$ values resulting from this test. We find a real scatter in both the age and the metallicity gradients which cannot be explained by the errors, in contrast with the findings of Mehlert et al. (2003). The difference may be due to the fact that the sample used by Mehlert et al. spans a more limited range in velocity dispersion ($2.2 < \log \sigma < 2.5$).

8.2. Correlation of the metallicity gradients in HDEGs with the central velocity dispersion

After Kobayashi (2004), the absence of correlation between the metallicity gradient and the central velocity dispersion may be the consequence of differences in the merger history of the galaxies. If the star formation processes in recent epochs have been less frequent in the Coma cluster galaxies, one might expect that any in situ correlation would have been impacted upon less substantially. To explore if this is the case, in Figure 13 we present the metallicity gradients measured in different $\Delta$index–$\Delta$index diagrams against the central velocity dispersion for the elliptical galaxies of the Coma cluster. The table at the bottom of the figure shows the results of a $t$-test and a non-parametric Spearman rank test to check the degree of correlation between both variables. In this case we find a correlation between the metallicity gradient and the central velocity dispersion, but only when the metallicity gradient is measured with the Fe4383 index. While the correlation is not statistically significant when derived from other indices, there does seem to be a marginal trend
in the sense that more massive galaxies also show a steeper gradient. To confirm this putative mass trend and further constrain galaxy formation models, higher signal-to-noise spectra must be obtained.

9. Conclusions

We have carried out a study of the gradients in 23 different spectral features for a sample of 82 early-type galaxies situated in different environments. Our results can be summarised thusly:

- Using the new synthesis stellar population models of V06 we have derived age and metallicity gradients for all the galaxies in the sample. We have used a new method with employs ten different indicators in order to reduce the scatter due to random errors.
- The mean age and metallicity gradients for the LDEGs are $\Delta [\text{M/H}]/\log r = -0.205 \pm 0.075$ and $\Delta \log (\text{age})/\log r = 0.082 \pm 0.032$, respectively. The mean age gradient is steeper and the mean metallicity gradient flatter, than the predictions of dissipative collapse models. On the other hand, the dispersion amongst the mean values is larger than the dispersion expected by errors alone.
- We have studied the metallicity gradients derived from different indicators, obtaining steeper gradients when using CN$_2$ and C4668 than with Fe4383 and Ca4227. Although it is beyond the scope of this paper to derive chemical abundances ratio gradients, we speculate that these aforementioned differences are reflecting the existence of radial variations in the relative abundances of some elements with respect to iron.
- We have studied the relation between the age and metallicity gradients and the gradient of velocity dispersion, finding a correlation when the metallicity gradient is calculated with CN$_2$ and Mgb. We do not, however, find a correlation when the metallicity gradient is derived from the Fe4383 and Ca4227 indices. The fact that the gradients of CN$_2$ and Mgb correlate with the gradient of the velocity dispersion may indicate that the gradients in some elements (e.g. N and Mg) were shaped early in the formation of galaxies, when the galactic winds presumably dominate. On the other hand, the lack of correlation when using Fe4383 and Ca4227 to measure the metallicity can indicate that other processes, such as secondary bursts of star formation, have had a stronger influence in the final shape of these gradients.
- We have not found any correlation between the metallicity gradients and the central velocity dispersion for the sample of galaxies in low-density environments. A strong correlation between the gradients and the mass of the galaxy is expected within dissipative collapse formation scenarios.
- We have found a significant correlation between the metallicity gradients and the central age for the LDEGs when the metallicity gradients are measured with Fe4383 and C4668, in the sense that galaxies with a younger central age also show a steeper metallicity gradient.
- The results quoted above suggest that the gradients of different chemical species may have formed by different mechanisms.
- The mean age and metallicity gradients for the galaxies in the Coma cluster are $\Delta \log (\text{age})/\log r = 0.027\pm0.138$ and $\Delta [\text{M/H}]/\log r = -0.328 \pm 0.157$, respectively. The mean value of the age gradient is compatible, to within the errors, with zero. Both values are also compatible with the predictions of Kobayashi (2004) for those galaxies which have not undergone major mergers. However, the dispersion amongst the mean values is higher than the scatter expected by the errors, indicative of real differences between galaxies.
- For galaxies in the Coma cluster, we have studied the correlation between the metallicity gradients and the central velocity dispersion finding a statistically significant correlation between both parameters when the metallicity is measured with Fe4383. For the other indices, the correlation is not statistically significant, but we observe a trend in the sense that more massive galaxies tend to have a steeper metallicity gradient. This trend is predicted by models of dissipative collapse, and was not found for the LDEGs. We should stress though that the quality of the data for the HDEGs is lower than that for the LDEGs; higher quality
data for the Coma cluster galaxies are urgently needed. In any case, in this paper we have found systematic differences between the stellar populations of galaxies in different environments which both confirms and extends our conclusions from Papers I and II.

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Fig. 13. Metallicity gradients versus central velocity dispersion for HDEGs. The different panels show the metallicity gradients obtained in different index–index diagrams (indicated between the brackets). The first panel (top left) compares the metallicity gradients obtained as described in Sec. 3. In the case in which the correlation is statistically significant, an error weighted linear fit is also shown. The table at the bottom indicates the results of a t-test and a non-parametric Spearman rank test (see text for details).
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