LINE STRENGTHS OF EARLY-TYPE GALAXIES* 

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ABSTRACT

In this paper we present measurements of velocity dispersions and Lick indices for 509 galaxies in the local universe, based on high signal-to-noise, long-slit spectra obtained with the 1.52 m ESO telescope at La Silla. The conversion of our measurements into the Lick/IDS system was carried out following the general prescription of Worthey & Ottaviani in 1997. Comparisons of our measurements with those of other authors show, in general, good agreement. We also examine the dependence between these indices (e.g., Hβ, Mg2, Fe5270, and NaD) and the central velocity dispersion (σ0), and we find that they are consistent with those previously reported in the literature. Benefiting from the relatively large size of the sample, we are able to investigate the dependence of these relations on morphology and environment, here represented by the local galaxy density. We find that for metallic lines these relations show no significant dependence on environment or morphology, except in the case of NaD, which shows distinct behavior for E and S0. On the other hand, the Hβ–log σ0 shows a significant difference as a function of the local density of galaxies, which we interpret as being caused by the truncation of star formation in high-density environments. Comparing our results with those obtained by other authors, we find a few discrepancies, adding to the ongoing debate about the nature of these relations. Finally, we report that the scatter of the Mg indices versus σ0 relations correlates with Hβ, suggesting that age may contribute to the scatter. Furthermore, this scatter shows no significant dependence on morphology or environment. Our results are consistent with the currently popular downsizing model, where low-mass galaxies have an extended star-formation history, except for those located in high-density regions.

Key words: galaxies: elliptical and lenticular, cD – galaxies: formation – galaxies: stellar content

Online-only material: machine-readable tables

1. INTRODUCTION

Efforts to understand how early-type galaxies formed and evolved have shown the importance of determining a group of fundamental parameters and investigating their relations. For instance, the study of their central velocity dispersions (σ0), luminosities (L), and characteristic sizes such as the effective radius (r_e), which reflect the influence of both dark and baryonic matter, has provided in the last few decades a deeper understanding of the structural and kinematic properties of this class of galaxies. Moreover, relations among these parameters such as those referred to as the Faber–Jackson (Faber & Jackson 1976) and the fundamental plane (Djorgovski & Davis 1987; Dressler et al. 1987) have proved to be important tools for the study of galaxy formation and evolution. In addition, their chemical enrichment can be addressed by means of colors or absorption line features of key elements such as Mg, Fe, and H Balmer lines. These can be compared to predictions of theoretical evolutionary single stellar population (SSP) models (e.g., Worthey 1994; Thomas et al. 2003), which summarize galaxies’ stellar-content properties, such as age and metallicity, along with distinct elements abundance ratios. In practice, line strengths have some advantages over colors because they are less affected by dust effects and are useful in breaking the so-called age–metallicity degeneracy, which prevents us from delivering a straight interpretation of galaxy light.

A particularly good example of the insight provided by line strength analysis, as well as the difficulties involved, can be seen from the analysis of the well-known Mg2–σ0 relation (e.g., Gorgas et al. 1990; Bender et al. 1993; Bernardi et al. 1998). This is usually interpreted as a mass–metallicity relation, since more massive galaxies are, in principle, able to retain larger amounts of enriched gas blown out in supernovae events, thus increasing the metallicity of the material from which new stellar generations are formed. By the same token, this class of objects should have an extended history of star formation, as predicted by both traditional scenarios of galaxy formation—the monolithic dissipative collapse (Larson 1974) and the hierarchical clustering (Kauffmann et al. 1993)—implying that the mass–metallicity relation should also be subject to age. Indeed, while this is, to some extent, true for early-type galaxies in general (Trager et al. 2000a), in the case of massive objects observational evidence conflicts with predictions, because they are essentially old (Kuntschner 2000) and had a short star-formation timescale, as indicated by the super-solar α/Fe ratio (Worthey et al. 1992; Thomas et al. 2005). On the other hand, low-mass objects have an extended star-formation history, which is currently known as downsizing (Cowie et al. 1996), or anti-hierarchical, since in the hierarchical clustering scenario they should be the first galaxies to appear and therefore be the oldest. Part of the answer to that inconsistency might be related to the details of the baryonic matter interactions, in the form of dissipation and galactic winds, driven by supernovae or active galactic nuclei (AGNs) (e.g., Pipino & Matteucci 2004; De Lucia et al. 2006).

While the Mg2–σ0 relation has proven to be extremely useful, the measurement of other line indices can provide additional information, such as age, formation timescale, and abundance, that may help discriminate among competing models of galaxy formation. The main goal of the present paper is to provide measurements for ten Lick indices for a representative sample of nearby early-type galaxies in order to characterize their
The present sample complements those recently available at intermediate redshifts such as the NOAO Fundamental Plane Survey (e.g., Nelan et al. 2005) and the Sloan Digital Sky Survey (SDSS), now a standard within $z = 0.3$ (e.g., Bernardi et al. 2005). While existing low-redshift samples (e.g., Thomas et al. 2005; Sánchez-Blázquez et al. 2006) are relatively small compared to those at intermediate redshifts, they have the advantage of having higher quality spectroscopic data and more reliable morphological and structural information.

This paper is organized as follows: in Section 2 we describe the sample selection and the observations in Section 3 the data reduction. In Section 4 we present the velocity dispersion measurements. The methodology used to compute line indices and the results of their comparison with those available in the literature are presented in Section 5. In Section 6 we analyze the index–log $\sigma_0$ relations and their dependence on galaxy morphology and environment. Finally, in Section 7 we present a summary of our conclusions.

2. THE SAMPLE AND OBSERVATIONS

The sample discussed here consists of objects extracted from the ENEAR catalog (da Costa et al. 2000). This survey contains a database of photometric (Alonso et al. 2003) and spectroscopic (Wegner et al. 2003) parameters for a magnitude limited ($m_B \leq 14.5$) sample of early-type galaxies which is considered representative of the nearby universe ($v_r < 7000$ km s$^{-1}$). Several global parameters are available in this database, such as magnitudes ($m_B$), the effective radius, mean surface brightness ($\mu_e$) within $r_e$, characteristic diameter ($D_e$), and the central velocity dispersion.

This sample includes objects residing in different environments such as the general field, groups, and clusters. As an additional criterion we excluded objects with $|b| \leq 15^\circ$ to avoid the galactic plane, and also objects with $\delta \geq 30^\circ$ due to the observational constraints. The observed list consists of 115 E, 131 E/S0, and 263 S0, giving a total of 509 galaxies, whose physical properties ($L$, $r_e$, $\sigma_0$) are fairly representative of the parent sample. In this paper we group, for analysis purposes, the galaxies E and E/S0 in the general class of E galaxies. These morphological types were revised based on visual inspection in two bands using images available in the Digital Sky Survey (Lasker et al. 1990). In Table 1 we display the catalog of observed galaxies, including some information about their physical properties. The columns in this catalog refer to (1) the object name, (2) and (3) (J2000.0) equatorial coordinates, (4) morphological type $T$, (5) apparent $B$-band magnitude $m_B$, (6) the heliocentric radial velocity $v_r$, and respective error in km s$^{-1}$, (7) the logarithm of $\sigma_0$ and its associated error in km s$^{-1}$ from our determinations (see Section 4), and (8) the logarithm of $r_e$ in units of kpc, based on the data of Alonso et al. (2003) and the $D_e$–$\sigma$ distances given by Bernardi et al. (2002). Finally, in Column 9, the number of companions $N_c$ as defined in Section 6.1 is presented. To give an idea of the global sample characteristics, the $v_r$, $m_B$, $\sigma_0$, and $M_B$ distributions are displayed in the panels of Figure 1.

The line strengths presented in this paper are based on long-slit spectra collected using the Boller & Chivens spectrograph mounted on the 1.52 m telescope at the La Silla site of the European Southern Observatory, during several runs between 1993 November and 2002 November. Our observations were carried out with a $4.1'' \times 2.5''$ slit centered on the galaxy nucleus using a TV guider. For the vast majority of the objects the spectrograph was rotated to allow the slit to be oriented along

![Figure 1. Distributions of $v_r$, $m_B$, $\sigma_0$, and $M_B$ for the galaxies of our sample.](image-url)

Table 1

| Name         | $\alpha$ (2000) | $\delta$ (2000) | $T$ | $m_B$ (km s$^{-1}$) | log $\sigma_0$ (km s$^{-1}$) | log $r_e$ (kpc) | $N_c$ |
|--------------|----------------|----------------|-----|-------------------|---------------------------|-----------------|-------|
| NGC 7832     | 00 06 28.5     | $-03 42 58$    | -3  | 13.50             | 6247                       | 2.340           | 0.096 | 0.725 | 6     |
| NGC 0050     | 00 14 44.7     | $-07 20 44$    | -3  | 12.50             | 5548                       | 2.413           | 0.020 | 0.750 | 6     |
| NGC 0113     | 00 26 54.7     | $-02 30 05$    | -3  | 14.00             | 4458                       | 2.185           | 0.046 | 0.356 | 9     |
| NGC 0125     | 00 28 50.4     | +02 50 23      | -2  | 13.83             | 5288                       | 2.064           | 0.094 | 0.539 | 11    |
| NGC 0155     | 00 34 40.1     | $-10 46 01$    | -3  | 14.00             | 6291                       | 2.250           | 0.051 | 0.700 | 11    |
| ESO 242G014  | 00 34 32.5     | $-43 39 22$    | -2  | 14.00             | 5940                       | 2.017           | 0.066 | 0.562 | 1     |
| NGC 0163     | 00 35 59.8     | $-10 07 19$    | -3  | 13.50             | 6028                       | 2.301           | 0.043 | 0.782 | 16    |
| NGC 0179     | 00 37 46.4     | $-17 51 01$    | -5  | 13.90             | 6004                       | 2.393           | 0.022 | 1     |
| NGC 0193     | 00 39 18.3     | $+03 19 53$    | -3  | 14.30             | 4441                       | 2.286           | 0.028 | 0.840 | 18    |
| MCG-01-03-018 | 00 50 27.6     | $-05 51 32$    | -3  | 13.50             | 5763                       | 2.279           | 0.043 | 0.631 | 2     |

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
the galaxy’s major axis. For some galaxies, observations were also done along the minor axis, and for a few of them the slit was oriented in an intermediate position. The typical exposure time was 10 min in the beginning of the survey, and 30 min at a later phase. More than one frame per object was frequently obtained, in particular for a set of ∼140 bright galaxies of the ENEAR sample selected to study metallicity gradients.

The various instrumental setups used are described in Table 2. The spectra were considered acceptable for the present analysis only if they had S/N > 20. The S/N was determined in the continuum range from 5860 Å to 5875 Å as the ratio between the average and the rms of the signal in that region. In Figure 2 we display the distribution of S/N for the observed galaxies. The typical resolutions are 3 Å and 6 Å (FWHM) as discussed below.

Dome flats and bias were taken on a nightly basis. The dark current was found to be negligible after all, and its correction was not applied. After each science target exposure, at the same position of the sky that the object was observed, arc lamps (He–Ar or He–Ar–Fe–Ne) were exposed for wavelength calibration. In addition, we observed radial velocity standard stars and stars in common with the Lick/IDS system, which are mainly in the F to K spectral-type range, with luminosity classes ranging from I to V. To determine the velocity dispersion of galaxies we restricted the sample of stars to G and K giants. Besides the calibration to the Lick/IDS system, all those standards allowed calibrations among different setups.

3. DATA REDUCTION

We followed standard procedures to reduce CCD spectra using IRAF. The science frames were subtracted by an average bias frame and divided by a normalized average flat-field frame. The 2D images had cosmic rays hits in the surroundings of the spectrum removed with the task \texttt{apall}. Those hits reaching the frame in the region next to the spectrum were not removed to avoid the introduction of artificial features. We also decided to discard the equivalent widths of lines which had cosmic rays within their definition range.

The extraction of 1D spectrum was made with the task \texttt{apall} setting the aperture to obtain as much of the galaxy’s light along the slit as possible. This means that the aperture size typically reached a radial distance from the galaxy’s center where the intensity is ∼5% of the peak value of the light profile. With this procedure we intended to obtain spectra containing as much information as possible of the galaxy as a whole, and not just from its central region.

Arc lamps observed after each object frame were used to provide wavelength solutions and spectra linearization. We adopted a fifth–seventh-order Legendre polynomial and the final fits used ∼20 and 50 lines with typical rms ∼0.02 and 0.08 Å, for the 1200 Å and 600 1 Å gratings, respectively. The wavelength solution was verified by checking that the sky lines (e.g., [O i]λ5577 Å) were located at their expected rest wavelength. The spectral resolution is ∼3 Å or ∼6 Å depending on the gratings used (see Table 2). No flux calibration was applied to the spectra.

4. MEASUREMENT OF $V_T$ AND $\sigma_0$

Radial velocity and velocity dispersions were measured for each spectrum using the cross-correlation technique (Tonry & Davis 1979). In particular, we used the RVSAO package (Kurtz & Mink 1998) to obtain $v_r$ by cross-correlating galaxy spectra with several templates. The velocity and error adopted was provided by the best template (largest correlation coefficient). The typical error for the $v_r$ measurement is ∼20 km s$^{-1}$.

For the measurement of $\sigma_0$ we generated a series of templates for each run/grating, combining stellar spectra of G and K giants since they represent the absorption features present in early-type galaxy spectra quite well. We used the wavelength interval from 4500 Å to 6000 Å, which is common to all the setups, to determine $\sigma_0$. Although this range encompasses the Hβ and NaD lines, which are suspected of providing poor fits, we tested different ranges, excluding one or both of them, finding no significant difference.

Another issue addressed in our procedure is the fact that the velocity dispersion varies with galactocentric radius. Global apertures, such as the ones we are using, do not sample systematically a characteristic size of the galaxy such as, e.g., some fraction of $r_e$, or some fixed size at the galaxy’s

![Figure 2. Distribution of S/N for the galaxies of our sample.](image-url)
ENEAR paper presented by Wegner et al. (2003). The results are also compared with those in the original (1998) and Wegner et al. (2003) work. Denicolé et al. (2005), and Sánchez-Blázquez et al. (2006). We sizes of circular and normalized apertures, respectively. The average value for Davies et al. and Sánchez-Blázquez et al. (2006) who observed with instrumental resolutions similar to ours. The small difference we find with Denicoló et al. (2005) is probably caused by their lower instrumental resolution of 6 Å. Trager et al. (1998) measurements also show good agreement over the entire range of σ0. Most of the data they present came from Davies et al. (1987), who used an instrumental resolution up to 85 km s⁻¹. Finally, we compare our measurements with those of the ENEAR catalog (Wegner et al. 2003), since we use a slightly different procedure to calculate σ0. The agreement is good, although the t value indicates that the offset is significant at the 95% confidence level, but not at the 90% level. It is worth mentioning that our sample includes new spectra with a better S/N, as compared to the data presented in Wegner et al. (2003).

5. ABSORPTION LINE MEASUREMENTS

The formal connection between observational data and stellar population models was initiated by Burstein et al. (1984) and Faber et al. (1985), who established the so-called Lick/IDS system, where central bandpass and flanking continua were defined for several absorption lines. To measure these indices for galaxies several procedures and calibrations are required, and in this section we describe them and also apply several tests to evaluate their quality. Later in this paper, we study the relations of these indices with σ0. We postpone to future papers the determination of the global stellar population parameters such as age, [Z/H] and α/Fe (R.L.C. Ogando et al. 2008a, in preparation), as well as their radial gradient (R.L.C. Ogando et al. 2008b, in preparation).

5.1. Definitions of Indices

The equivalent widths W were measured for two kinds of features: atomic absorption lines (Wa, expressed in Å) and molecular bands (Wm, in magnitudes). Their general expressions are given by the equations:

\[ W_a = \left(1 - \frac{\int_{\lambda_1}^{\lambda_2} F(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} C(\lambda) d\lambda}\right) (\lambda_2 - \lambda_1) \]

\[ W_m = -2.5 \log \left(\frac{\int_{\lambda_1}^{\lambda_2} F(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} C(\lambda) d\lambda}\right) \]

where \( F(\lambda) \) is the line flux, \( C(\lambda) \) is the continuum flux, and \( \lambda_1 \) and \( \lambda_2 \) are the wavelengths defining the interval within which \( F(\lambda) \) and \( C(\lambda) \) are calculated.

Statistical errors in the indices \( W_a \) and \( W_m \) were calculated, respectively, according to the following expressions:

\[ \epsilon_{W_a} = \sqrt{\left(\frac{1}{\int_{\lambda_1}^{\lambda_2} F(\lambda) d\lambda} \right)^2 \epsilon_F^2 + \left(\frac{\int_{\lambda_1}^{\lambda_2} F(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} C(\lambda) d\lambda}\right)^2 \epsilon_C^2} \times (\lambda_2 - \lambda_1) \]

\[ \epsilon_{W_m} = 2.5 \left[\left(\frac{1}{\int_{\lambda_1}^{\lambda_2} F(\lambda) d\lambda}\right)^2 \epsilon_F^2 + \left(\frac{1}{\int_{\lambda_1}^{\lambda_2} C(\lambda) d\lambda}\right)^2 \epsilon_C^2\right]^{1/2} \]
Table 4
Line Index Definitions

| Index | Bandpass (Å) | Blue pseudocontinua (Å) | Red pseudocontinua (Å) | Units |
|-------|--------------|--------------------------|------------------------|-------|
| Hβ   | 4847.87      | 4876.62                  | 4827.87                | 4847.87 4876.62 4891.62 Å |
| Fe5015 | 4977.75      | 5054.00                  | 4977.75                | 5054.00 5065.25 Å |
| Mg1  | 5069.12      | 5134.12                  | 4946.50                | 5301.12 5366.12 mag |
| Mg2  | 5154.12      | 5196.62                  | 4957.62                | 5301.12 5366.12 mag |
| Mgβ | 5160.12      | 5192.62                  | 5161.37                | 5191.37 5206.37 Å |
| Fe5270 | 5245.65      | 5285.65                  | 5233.15                | 5285.65 5318.15 Å |
| Fe5335 | 5312.12      | 5352.12                  | 5304.62                | 5353.37 5363.37 Å |
| Fe5406 | 5393.54      | 5316.54                  | 5391.37                | 5415.00 5425.00 Å |
| NaD  | 5876.87      | 5909.35                  | 5860.62                | 5922.12 5948.12 Å |
| [O iii]5007 | 4996.85      | 5016.85                  | 4885.00                | 5030.00 5070.00 Å |

Note. The [O iii]5007 index is used to estimate the emission level in the spectra.

Figure 4. The galaxy NGC 7507 is taken as an example of the typical spectra in each of the setups mentioned in Table 4. The setup identification number is shown at the left side of each spectrum. No flux calibration was applied.

Figure 5. Measurements of the FWHM for lines in arc lamp spectra for 1200 l mm$^{-1}$ (triangles) and 600 l mm$^{-1}$ (squares) gratings. It is also shown the Lick/IDS resolution as given by Worthey & Ottaviani (1997) (continuous line).

where $\epsilon_F$ and $\epsilon_C$ are the rms values for the central and continuum features of the line measured. We have determined, for each galaxy, all the set of Lick indices within the observed spectral range. However, to define the final set of indices considered we took into account two conditions: a common spectral coverage to all observing setups and the variation of the fractional error of a given index with S/N. The different sensitivity functions produced by the combination of CCD and grating resulted in better determination of some indices than others. In particular, the blue indices measurements are poor, as they are in a region of low detector and grating efficiency. In Table 4 we list the indices measured with their passband and pseudo-continua definitions. We also include the [O iii]5007 line definition as given by González (1993), although it is not defined in the Lick system. This index is used to identify and discard undesired emission contaminated spectra, as discussed below.

In Figure 4 we show, as an example, the spectra for NGC 7507 as observed with each instrumental setup. Note that the spectrum shape in configuration 1 is quite different from the others. In order to verify the impact that this may have using spectra that have not been flux calibrated we have used a subsample of galaxies for which flux calibration is available. We have then compared the line index measurements carried out in both subsets. We find that for the molecular indices Mg1 and Mg2 there is indeed a significant difference (as estimated from a Student t test). This is not unexpected since the continua definition for these indices is far from the central passband. In the next section we discuss this issue and the procedure to remove this effect.

5.2. Calibrations of Indices

5.2.1. Correction to the Lick Resolution

Since we have a higher resolution than that of the Lick/IDS system, before calculating indices, we degrade our spectra in resolution to match that of the Lick/IDS system by convolving the spectra with a Gaussian function with an appropriate width, as described by Worthey & Ottaviani (1997). In order to determine our resolution we fitted Gaussian functions to lines of the wavelength calibration arc lamps. This procedure allowed us to estimate the resolution variation along the entire wavelength range. Figure 5 shows the measured FWHM for several lines for the two gratings used. For comparison, we plot the Lick resolution curve described by Worthey & Ottaviani (1997). It is important to consider this effect since some of the indices (e.g., Mgβ, Fe5270, Fe5335) are very sensitive to resolution. An IRAF task named lickleqv was created to carry out the degradation and also measure equivalent widths.
Despite the conversion of our observed spectra to the Lick/IDS resolution, this is not enough to fully transform our data to that system. Small zero-point residuals still persisted. Offsets were then calculated for each of the instrumental setups described in Table 2 using the same group of 21 stars of spectral types F to K and luminosity classes from I to V. This is true except for setup 1, which had only 9 stars in common with the others setups. In this case, we estimated the offset relative to setups 2 and 3, which had already been corrected to the Lick system. The choice of a homogeneous set of stars is important since variations in the offset amongst setups are produced by the use of different samples of stars. This is probably associated with internal systematic uncertainties in the Lick system. Spectra of M stars were available but were not included because of their non-monotonic behavior with resolution degradation.

The offsets computed as described above were applied to the indices calculated for galaxies, after the corrections described in the next two sections, as a last step to perform the transformation to the Lick system. Afterwards, as a final verification, we looked for any residual offset in the galaxies line strength measurements between setups. Only Mg1 and Mg2 have shown a significant offset between setup 1 and the others. As mentioned in Section 5.2, this is probably related to the lack of flux calibration. This offset was taken into account and the results show that we ended up with a homogenous system of line strength measurements that is appropriate for stellar population analysis.

5.2.2. Correction for Velocity Dispersions

The stellar velocity dispersion in a galaxy causes a spillover of line flux outside the narrow central bandpass, as it was defined originally for stars. To compensate for this effect we measured line strengths in artificially broadened spectra of G and K giants. We simulate velocity dispersions in the range 50–500 km s\(^{-1}\) with steps of 30 km s\(^{-1}\). This was done using a modified version of the gauss task of the IRAF package, where the Gaussian dispersion is expressed in pixels, so that the transformation to km s\(^{-1}\) can be done by the relation:

\[
\sigma = c \frac{\delta \lambda}{\lambda} \sigma_{\text{pixels}} \quad (6)
\]

where \(c\) is the velocity of light, and \(\lambda\) is a reference wavelength (5400 Å). The values of the spectral dispersions are \(\approx 1\) Å and \(\approx 2\) Å for the 12001 mm\(^{-1}\) and 6001 mm\(^{-1}\) gratings, respectively.

Measurements of indices in stellar spectra artificially broadened permit the calibration of a relation between the broadening effect on the indices, \(F(I)\), and \(\sigma\). For atomic indices the relation is \(F(I) = I(0)/I(\sigma)\), while for molecular indices it is \(F(I) = I(\sigma) - I(0)\), where \(I(\sigma)\) is the index strength at a given \(\sigma\) and \(I(0)\) is the index measured in the original spectrum. Functions \(F(I)\) for each index and grating were generated from third-order polynomial fits to these relations for a group of stars of types G to K according to the expression

\[
F(I) = \sum_{i=0}^{3} A_i (\log \Delta \lambda) ^i. \quad (7)
\]

In Figure 6 we display these functions for each measured index for both gratings of 12001 mm\(^{-1}\) and 6001 mm\(^{-1}\). Qualitatively, this correction agrees well with others presented in the literature (e.g., Trager et al. 1998; Kuntschner 2000). For example, the amount of correction is very small for broad indices such as Mg2, but large for narrow indices such as Fe5270 and Fe5335, reaching \(\approx 30\%\) for galaxies with 300 km s\(^{-1}\). Another point is that the H\(\beta\) index is very sensitive to the choice of stellar spectral type into the definition of \(F(I)\), as already pointed out by Kuntschner (2000), producing sometimes values of \(F(I)\) smaller than 1. The causes for this behavior are that the H\(\beta\) itself fades very quickly as the temperature gets lower, and a TiO band head (\(\approx 4851\) Å) starts to appear in low-temperature stars (Schiavon et al. 2002). For this reason, in the particular case of the H\(\beta\) index, some of the lowest-temperature stars are not included in the fit. Quantitatively, the average difference of \(F(I)\) at the arbitrary value of \(\sigma = 300\) km s\(^{-1}\) is about 1 \(\pm\) 3% for the indices in common with Trager et al. (1998), with the exception of Mg1 and Mg2. For the Mg indices they use a multiplicative factor instead of an additive one, thus not allowing a comparison.

5.2.3. Correction by Aperture

The indices calculated as described above do not refer to a fixed metric aperture or to some fraction of \(r_e\), implying that we sample differently the galaxies, as described in Section 3. Since the distribution of chemical elements inside the galaxy is not homogeneous, we need to correct them to some fiducial aperture in a similar way to what was done for \(\sigma_{\text{e}}\) in Section 4. Here, we also consider an average gradient, this time for line strengths, which are all measured in magnitudes, even in the case of atomic indices, so that they are converted from Å (I) to magnitudes (I’) according to the equation

\[
I’ = -2.5 \log \left( 1 - \frac{I}{\Delta \lambda} \right) \quad (8)
\]
where $\Delta \lambda$ is the central passband of the index. Then we derived a fiducial aperture corrected index ($I_{\text{norm}}$) given by

$$I_{\text{norm}}' = I_{\text{norm}}' - \beta \log \left( \frac{r_{\text{ab}}}{r_{\text{norm}}} \right)$$

where $r_{\text{ab}}$ and $r_{\text{norm}}$ have the same meaning as in Equation (1), and $\beta$ is the average radial gradient for each index, which is presented in Table 5. The parameter $\beta$ is the angular coefficient of a straight line fitted to the $I'(r)$ profile as a function of $\log(r/r_*)$, where $r_*$ is the galaxy’s effective radius corrected for its ellipticity. A full description of this parameter and its determination will be presented in R.L.C. Ogando et al. (2008b, in preparation).

### 5.2.4. Emission Contamination

Early-type galaxies may contain some amount of ionized gas and young stars, which may lead to the presence of emission lines and contamination of their old population spectra (e.g., Macchetto et al. 1996). In these cases, some line indices may be significantly affected by these emission features, in particular $H\beta$ and Fe5015 (by the [O III]λ5007 line). Indeed, even if the emission is not strong, it may partially fill the $H\beta$ line, resulting in a smaller value for its measured equivalent width and as a consequence, causing ages to be overestimated when using SPP models (Trager et al. 2000). A possible way to correct for the $H\beta$ contamination can be accomplished if we can infer the contribution from another emission line. For the case of $H\beta$, González (1993) derived a relation between the emission contamination in this line and the [O III]λ5007 equivalent width, established by the emission-free stellar spectra fit to those galaxies in his sample. He found that the amount of emission contamination in $H\beta$ is given by $\Delta H\beta = 0.6 \times [\text{O III}]\lambda 5007$. However this correction has a considerable uncertainty and should be taken as a statistical approach since the $H\beta$/[O III]λ5007 ratio varies considerably from galaxy to galaxy.

Another possible way to deal with the emission contamination in the $H\beta$ index is to infer it through the intensity of Hα line (e.g., Nelan et al. 2005; Denicoló et al. 2005). However, due to the different spectral coverage associated with the several instrumental setups used, we are able to measure Hα for only one third of the sample. Thus, instead of using these statistical corrections, we decided to exclude from the analysis galaxies with measurable emission of [O III]λ5007 at a detection level larger than twice its rms error. This condition affects 18 galaxies, or about 4% of the sample, which is a smaller fraction than that of 12% found by Nelan et al. (2005) for galaxies selected on the basis of red sequence criteria which may include some early-type spirals, since no explicit morphological segregation was imposed. The galaxies with detected emission are predominantly S0 (11 galaxies), and they are distributed evenly among the distinct environments. We illustrate the impact of this rejection criterion on the distribution of [O III]λ5007 and $H\beta$ intensities in Figure 7, where we note that even galaxies with positive $H\beta$ indices are excluded from the sample, showing how subtle the emission contamination can be.

### 5.3. Internal Comparison

For objects with several observations, the final value for an index was computed by (1) applying to each available measurement all the calibrations and corrections mentioned above, (2) computing the mean of all measurements, (3) discarding outliers with values $2\sigma$ above the average, and (4) re-computing the mean one more time. The final values for the indices of all the 509 galaxies are presented in Table 6, including those with emission lines which are not included in the analysis below. Besides the statistical error determination described in Section 5.1, we need to take into account other sources of uncertainties such as, for example, those related to wavelength calibration, sky background subtraction, position angle of the slit over the galaxy, the fraction of galactocentric radius encompassed by the slit. Multiple observations ($N > 2$) are available for 91 galaxies ($\approx 18\%$) of our sample, and they are used to estimate a more representative error for our line strengths. We calculated for each line index an average of the fractional error combining the individual determinations. In Table 7 we present the statistics of this averaging process and it can be noted that, in general, the errors derived from multiple observations reach

### Table 5

| Index   | $\beta$       |
|---------|---------------|
| $H\beta$| 0.002 ± 0.027 |
| Fe5015  | -0.012 ± 0.027 |
| Mg2     | -0.033 ± 0.026 |
| Mg2     | -0.055 ± 0.035 |
| Mg2     | -0.031 ± 0.034 |
| Fe5270  | -0.016 ± 0.025 |
| Fe5335  | -0.012 ± 0.027 |
| Fe5406  | -0.015 ± 0.029 |
| Fe5709  | -0.000 ± 0.036 |
| NaD     | -0.034 ± 0.022 |

Figure 7. Distribution of [O III]λ5007 (top panel) and $H\beta$ (bottom panel) before (dotted line) and after (solid line) discarding galaxies with detected emission.

![Figure 7](image-url)
5–10% of the index value, while errors from individual measurements are typically 1–3% of the index value. In Figure 8 we display measurements of indices for galaxies with more than ten observations in order to show the range of their fluctuations. Thus, based on the statistics shown in Table 7 we claim that, in general, our errors are less than 10% of the index value.

5.4. Comparison with Other Authors’ Results

To evaluate the overall quality of our data and calibrations, we have compared our measurements of line indices with those from measurements reported in the literature by other authors of samples having a significant number of overlaps with ours. The results of these comparisons are shown in Table 8 and Figures 9–13. Table 8 gives; in Column 1 the index; in Column 2 the number of galaxies in common $N_{\text{gal}}$; in Column 3 the mean difference $\langle \delta I \rangle$ and its rms; and in Column 4 the $t$ value of the Student test. We recall that for $t > 1.96$, the differences are considered significant at a 95% confidence level.

| Name         | Hβ | Fe5015 | Mg_b | Fe5270 | Fe5335 | Fe5406 | Fe5709 | NaD   | [O III] |
|--------------|----|--------|------|--------|--------|--------|--------|-------|--------|
| NGC 7832     | 1.03 | 5.143 | 0.132 | 0.309 | 4.653 | 2.820 | 2.382 | 1.859 | 0.792 | 4.518 | 0.613 |
| NGC 0050     | 1.375 | 5.533 | 0.137 | 0.303 | 4.688 | 2.963 | 2.738 | 1.610 | 0.642 | 4.573 | 0.767 |
| NGC 0113     | 1.984 | 4.747 | 0.110 | 0.256 | 4.196 | 2.905 | 2.708 | 1.309 | 1.204 | 3.004 | 0.959 |
| NGC 0125     | 1.825 | 4.464 | 0.153 | 3.199 | 2.620 | 2.110 | 1.979 | 0.883 | 3.403 | 0.368 |
| NGC 0155     | 1.713 | 5.296 | 0.121 | 0.262 | 3.897 | 3.155 | 2.703 | 1.736 | 0.627 | 3.742 | 1.098 |

Note. The index [O III] in Column 12 refers to the line of [O III] 1038.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

Table 7

| Index | Average | Median | Lower quartile | Upper quartile |
|-------|---------|--------|----------------|----------------|
| Hβ    | 0.103   | 0.071  | 0.085          | 0.044          | 0.151 |
| Fe5015| 0.085   | 0.059  | 0.074          | 0.037          | 0.123 |
| Mg_b  | 0.062   | 0.051  | 0.048          | 0.023          | 0.093 |
| Mg2   | 0.036   | 0.034  | 0.025          | 0.010          | 0.055 |
| Mg_b  | 0.046   | 0.031  | 0.045          | 0.020          | 0.063 |
| Fe5270| 0.071   | 0.053  | 0.053          | 0.038          | 0.096 |
| Fe5335| 0.081   | 0.054  | 0.071          | 0.042          | 0.117 |
| Fe5406| 0.087   | 0.055  | 0.076          | 0.052          | 0.115 |
| Fe5709| 0.112   | 0.071  | 0.103          | 0.048          | 0.162 |
| NaD   | 0.045   | 0.035  | 0.037          | 0.022          | 0.058 |

Notes. The values quoted in the table refer to the distribution of final fractional errors distribution. This is done combining several measurements for the same galaxy on different occasions or with distinct setups.
Figure 8. Scattering of line indices for galaxies with more than ten observations. The panels show the fractional errors \((I - \langle I \rangle)\) for the various line indices versus the average line index \((\langle I \rangle)\). The horizontal error bars indicate the error of each individual measure.

Figure 9 shows a comparison with Trager et al. (1998), which includes the original Lick/IDS data. Despite the lower quality of the data, we find from Table 8 that the agreement is very good. The same is true regarding the comparison with Trager et al. (2000a) (Figure 10) which reports data of better quality obtained by González (1993). The only exception is the Fe5270 index. More recently, new data have been presented by Denicoló et al. (2005) and Sánchez-Blázquez et al. (2006). Comparisons with their measurements are shown in Figures 11 and 12. We find that in general the agreement is good, except for the Fe indices measured by Denicoló et al. (2005). In the case of Sánchez-Blázquez et al. (2006) only the Fe5015 presents a more discrepant result. Finally, in Figure 13 we compare our measurements of the Mg\(_2\) index with those presented earlier in Wegner et al. (2003) for \(\approx 400\) galaxies in common, but occasionally using new spectra with better S/N. We note that in the present paper we use a slightly different method to estimate the pseudo-continuum on each side of the band trying to correct for the local inclination of the spectra. The quantitative results are given in Table 8, from where we find that the agreement is excellent.

We also mention that in the last few years large surveys similar to the one being reported here have been conducted (e.g., Nelan et al. 2005; Colless et al. 2001), but unfortunately the number of objects in common is too small (<3) to allow a comparison.

In summary, based on the results presented above, we conclude that, in general, our measurements of line index are in good agreement with those available in the literature. Occasionally, some significant discrepancies are detected for a particular index, but this does not seem to reflect a systematic problem as it varies from author to author. Instead, they probably reflect different effects that may affect the measurement such as differences in the region of the galaxy sampled (e.g., different position angle and/or radial extent), lack of a suitable set of stars used to calibrate the Lick system by some authors, and the details of the procedure adopted for estimating the correction due to velocity dispersion and resolution.

6. INDICES, MASS, VELOCITY DISPERSION, AND ENVIRONMENT

A connection between dynamical and chemical properties of early-type galaxies may be established through relations between the strength of line indices and their velocity dispersions or masses, as for example the well-known Mg\(_2\)–\(\sigma_0\) relation. Since our data constitute one of the largest samples of early-type galaxies with good spectral quality and resolution at \(z \approx 0\), we investigate not only this but similar relations for other lines
taking into account different morphologies and environments. In order to do that, we first define environment and mass estimators for our galaxies as described below.

6.1. Characterizing the Galaxy Environment

Although early-type galaxies are found more frequently in clusters and groups of galaxies, their relative quantity to other morphological types depend essentially on the local density of galaxies. This behavior is translated in the well-known “morphology–density” relation (e.g., Dressler 1980; Maia & da Costa 1990). Taking this into account, we decided to characterize the environment for a galaxy estimating the number of companions brighter than a fixed absolute magnitude, within a given “box” size. This is equivalent to calculating the density

![Figure 9. Comparison between galaxies’ indices measured by Trager et al. (1998) and our results (O08).](image-url)

| Sample   | N_{gal} | (log σ_0) | Skewness | Kurtosis | (log M_0) | Skewness | Kurtosis |
|----------|---------|-----------|----------|----------|-----------|----------|----------|
|          |         | (km s^{-1})|          |          | (M_⊙)    |          |          |
| (1)      | (2)     | (3)       | (4)      | (5)      | (6)       | (7)      | (8)      |
| E total  | 226     | 2.30 ± 0.15| −0.38    | 1.92     | 10.79 ± 0.52| −0.32     | 0.86     |
| S0 total | 230     | 2.21 ± 0.18| −0.43    | 1.02     | 10.51 ± 0.59| −0.06     | 0.01     |
| E LD     | 49      | 2.28 ± 0.13| −0.38    | 3.24     | 10.73 ± 0.49| −0.45     | 1.97     |
| E MD     | 116     | 2.32 ± 0.12| −0.12    | −0.07    | 10.85 ± 0.43| 0.14      | −0.11    |
| E HD     | 61      | 2.27 ± 0.20| −0.87    | 0.20     | 10.72 ± 0.67| −0.77     | −0.45    |
| S0 LD    | 71      | 2.22 ± 0.15| −0.09    | 1.12     | 10.52 ± 0.52| −0.02     | −0.55    |
| S0 MD    | 98      | 2.21 ± 0.18| −0.72    | 1.80     | 10.53 ± 0.58| −0.19     | 0.53     |
| S0 HD    | 61      | 2.18 ± 0.20| −0.44    | −0.35    | 10.46 ± 0.69| −0.06     | −0.52    |
of objects, being more representative of the local environment around an object than just classifying it as a field, group, and cluster galaxy.

In order to estimate the number of neighbors ($N_c$) for each galaxy in our sample, we used the catalog of galaxies available in the HyperLeda database (Paturel et al. 2003), which has a larger sky coverage than the Southern Sky Redshift Survey (da Costa et al. 1998), for example. Although the former represents a compilation, it is considered complete down to $m_B \approx 15.5$. A galaxy from this catalog contributes to the neighborhood counts of a given galaxy in our sample, if it satisfies the following criteria: (i) the difference between their radial velocities is $< 750$ km s$^{-1}$, (ii) their projected separation is $< 500$ kpc, and (iii) the HyperLeda galaxy has $M_B < -16.0$. It should be mentioned that there is no strong bias of $N_c$ with distance as can be seen in Figure 14. The distribution of $N_c$ for our sample divided by morphological type is displayed in Figure 15. We note that this density indicator has a wide dynamical range, making it sensitive to variations from the external to central regions of clusters and to the mean cluster density. This can be seen in Figure 15 where we indicate in the plot the position occupied by a galaxy in the central part of the Fornax cluster (medium density) and from one in the central part of the Virgo cluster (high density). This indicates that this classification scheme is more meaningful than the usual field/group/cluster one, as used by Bernardi et al. (1998), for instance.

The median value for the $N_c$ distribution in the volume considered is 10 galaxies and the lower and upper quartiles are $Q_L = 4$ and $Q_U = 22$ galaxies, respectively. Taking these values into account, we divided the sample into three intervals of densities: low density (LD; $N_c \leq 4$), medium density (MD; $4 < N_c < 22$), and high density (HD; $N_c \geq 22$). Our main goal in splitting the sample in this way is to compare the two extreme environments, LD and HD, using about the same number of objects in each of them, so that we can avoid misleading statistical inferences. Among the 509 galaxies of our sample, only two galaxies were considered isolated ($N_c = 0$) according to the prescribed criteria. Examining $N_c$ for 11 galaxies in common with the isolated sample of Reda et al. (2004), only three have $N_c > 2$. Among them, NGC 1132, that is the galaxy with the greatest $N_c$ (11 companions), has an associated extended X-ray emission typical of groups of galaxies. Indeed this galaxy is considered a “fossil group” by Mulchaey & Zabludoff (1999), and if we inspect DSS images, it is possible to see fainter galaxies around this object. We also note that among the criteria adopted by Reda et al. (2004) there is one that excludes companions that are 2 mag fainter than that of the target object, what could explain this case.

### 6.2. Galaxy Mass Estimators

The mass of a galaxy is one of its fundamental parameters and its determination may follow different recipes. The most common estimator is the central velocity dispersion $\sigma_0$ which, in fact, probes the gravitational potential. Another mass estimator comes from the consideration that the object is in dynamical equilibrium, satisfying the virial theorem. Thus, the mass $M_e$ in units of $M_\odot$ is given according to Burstein et al. (1997) by the expression

$$\log M_e = \log (\sigma_0^2 \, r_e) + 5.67$$  \hspace{1cm} (10)

where $r_e$ is the galaxy effective radii in units of kpc.

In both cases it is implicit that the contribution by rotation to the object’s dynamical support is assumed to be negligible. Another point of concern is related to the conversion of $r_e$ in
arcseconds to kpc which needs a reliable determination of the galaxy distance ($D$). Considering just the redshift to calculate $D$, we may incur in error due to the peculiar motion of galaxies. Thus, we adopted $D$ given by the $D_n - \sigma$ relation (Bernardi et al. 2002) to calculate $r_e$ in kpc.

Since in the next section we discuss the relations between indices and mass for the sample divided in different morphologies and environments, it is interesting to inspect beforehand the differences in the mass distribution of these particular subsets. We show in Figure 16 these distributions using both estimators described above, according to distinct morphological type. In Table 9 we present mean values, dispersion, skewness, and kurtosis for these estimators. Also, in Table 10 we show the probability that the samples of E and S0 galaxies have the same parent population as given by the Kolmogorov–Smirnov (K-S) test. For both mass estimators, these samples have very different distributions, where the mass distribution of E galaxies is skewed toward higher masses as compared to the one for S0s. We investigate below if this behavior implies different index $- \log \sigma_0$ relations for distinct morphologies.

We also use the environment definitions described above to divide the mass distribution of E and S0 galaxies, as shown in Figures 17 and 18, respectively. These plots, which reflect the morphology–density relation, stress that the most massive Es are located in high-density environments, but S0s do not follow this trend, having similar mass distribution in all environments.

It is noticeable in Figure 17 and also from the computed values of kurtosis and skewness in Table 10, that the mass distribution of E galaxies in HD is less peaked and more concentrated toward the high mass end of the distribution than those in the LD environment. For the S0s, such a trend occurs more slightly and, in particular, for $\log M_e$, the similarities between the shape parameters and the higher K-S probability (40%) indicate that S0s have almost the same mass distributions in different environments.

This observed mass distribution of E galaxies is expected by hierarchical clustering models, where higher-mass objects are formed in denser regions (Lemson & Kauffmann 1999), and most of them turn out to be Es in numerical simulations (Springel et al. 2001). On the other hand, this result can be interpreted as an evolutionary difference if Es are the product of a faster and older process of growth of spheroids through dissipationless mergers or coherent collapse, while lenticulars may be formed at least partially, from stripping of spirals by strong two-body gravitational interactions (Dressler et al. 1997). We should take this fact into
account when interpreting the index—log $\sigma_0$ relations in the next section.

6.3. Index–log $\sigma_0$ Relations

The first well-established relation between an index and $\sigma_0$ was set for the $\text{Mg}_2$ index (e.g., Terlevich et al. 1981; Dressler et al. 1987; Bender et al. 1993; Bernardi et al. 1998), which is generally interpreted as a relationship between mass and metallicity. However, there is some debate about the true nature of this relation, which might be influenced by stellar ages or variations in abundance ratios, for instance that of $[\alpha/\text{Fe}]$. In particular, for a given mass, the small scatter of the $\text{Mg}_2$–log $\sigma_0$ relation has also been attributed to a “conspiracy” between metallicity and age (Trager et al. 2000b), in the sense that older galaxies are less rich in metals. Thus, it is important to investigate the index–log $\sigma_0$ relations for other elements, whose slopes and scatter should be sensitive to different chemical composition variations.

In the discussion below, we present all of our measured indices ($I'$) in magnitudes ($I'$), using the transformation given by Equation (8), in order to permit the comparison with the work of other authors. The $I'$–log $\sigma_0$ relations for ten measured indices, separating galaxies by morphology (E and S0), are shown in Figure 19. The lines in the Figure represent the best fit, $I' = A + B \log \sigma_0$, to the data. The parameters of the fits and their associated errors are presented in Table 11, which also gives the number of galaxies ($N_{gal}$) used in the fit, the Spearman rank $r_s$ coefficient and the $t$ parameter, which tests the null hypothesis ($B = 0$). We recall that a value of $t > 1.96$ means that the slope ($B$) is significantly different from zero. We stress that our data were obtained using a long slit and each spectrum represents a light-weighted measurement, reflecting the mean stellar population contributing to most of the galaxy’s light.

From Figure 19 and Table 11 we find that, in general, there is a significant correlation between the metallic indices and $\sigma_0$, as indicated by the rank coefficient $r_s$, which is specially strong for the Mg and NaD lines. The Fe lines, on the other hand, tend to have a moderate correlation with $\sigma_0$. The only exception is the $\text{Fe}5709'$ index which, in agreement with Clemens et al. (2006), shows no correlation. This behavior is probably due to the weak dependence of this Lick index on Fe abundance, as discussed by Korn et al. (2005). We point out that, in contrast to our result and the one reported by Nelan et al. (2005), Clemens et al. (2006) also finds no correlation for the $\text{Fe}5270'$ index.

Figure 12. Comparison between galaxies' indices measured by Sánchez-Blázquez et al. (2006) and our results (O08).
The NaD’ line shows a correlation with $\sigma_0$ as significant as that of the Mg lines (see also Clemens et al. 2006), but its known dependence on interstellar absorption hampers a reliable interpretation. While S0s may be affected, one should not expect a strong contribution from the ISM in a “dust-free” object like an E galaxy.

Finally, Figure 19 shows that the Balmer line Hβ’ is the only one that decreases with increasing $\sigma_0$ (anti-correlates). This result is consistent with several previous works (e.g., Trager et al. 1998; Denicoló et al. 2005; Sánchez-Blázquez et al. 2006; Clemens et al. 2006).

In order to verify possible differences of the $I'$–$\sigma_0$ relation between E and S0 galaxies, we compare in Figure 20 the linear fit coefficients (Table 11) obtained for these two sub-samples.

### Table 12

Results from the $I'$–$\log \sigma_0$ Linear Fits for Different Environments

| Index | $A$   | $B$   | $N_{rad}$ | $r_f$ | $t$   |
|-------|-------|-------|-----------|-------|-------|
| $H\beta$ | $0.212 \pm 0.023$ | $-0.067 \pm 0.010$ | 123 | $-0.45$ | $-5.53$ |
| Fe5015 | $0.033 \pm 0.016$ | $0.018 \pm 0.007$ | 124 | 0.17 | 1.87 |
| MgI   | $-0.167 \pm 0.033$ | $0.130 \pm 0.014$ | 117 | 0.61 | 8.23 |
| MgII  | $-0.200 \pm 0.046$ | $0.208 \pm 0.020$ | 125 | 0.63 | 9.05 |
| MgII  | $-0.148 \pm 0.024$ | $0.131 \pm 0.010$ | 124 | 0.72 | 11.31 |
| Fe5270 | $0.036 \pm 0.013$ | $0.021 \pm 0.006$ | 125 | 0.23 | 2.62 |
| Fe5555 | $0.017 \pm 0.014$ | $0.024 \pm 0.006$ | 123 | 0.30 | 3.51 |
| Fe5406 | $0.016 \pm 0.014$ | $0.025 \pm 0.006$ | 124 | 0.26 | 2.92 |
| Fe5709 | $0.042 \pm 0.010$ | $0.001 \pm 0.004$ | 118 | 0.01 | 0.08 |
| NaD   | $-0.168 \pm 0.031$ | $0.139 \pm 0.014$ | 126 | 0.64 | 9.32 |

| Low density |
|-------------|
| $H\beta$ | $0.163 \pm 0.014$ | $-0.045 \pm 0.006$ | 226 | $-0.43$ | $-7.13$ |
| Fe5015 | $0.037 \pm 0.010$ | $0.018 \pm 0.004$ | 232 | 0.24 | 3.83 |
| MgI   | $-0.185 \pm 0.019$ | $0.141 \pm 0.008$ | 226 | 0.72 | 15.73 |
| MgII  | $-0.211 \pm 0.028$ | $0.217 \pm 0.012$ | 235 | 0.76 | 17.90 |
| MgII  | $-0.139 \pm 0.015$ | $0.128 \pm 0.007$ | 235 | 0.77 | 18.38 |
| Fe5270 | $0.031 \pm 0.007$ | $0.023 \pm 0.003$ | 235 | 0.38 | 6.31 |
| Fe5555 | $0.001 \pm 0.008$ | $0.032 \pm 0.004$ | 235 | 0.39 | 6.53 |
| Fe5406 | $0.015 \pm 0.009$ | $0.026 \pm 0.004$ | 233 | 0.30 | 4.73 |
| Fe5709 | $0.044 \pm 0.007$ | $0.000 \pm 0.003$ | 230 | $-0.03$ | $-0.46$ |
| NaD   | $-0.251 \pm 0.021$ | $0.177 \pm 0.009$ | 234 | 0.76 | 17.61 |

| Medium density |
|----------------|
| $H\beta$ | $0.156 \pm 0.013$ | $-0.042 \pm 0.006$ | 120 | $-0.56$ | $-7.43$ |
| Fe5015 | $0.053 \pm 0.010$ | $0.011 \pm 0.004$ | 124 | 0.21 | 2.43 |
| MgI   | $-0.159 \pm 0.020$ | $0.131 \pm 0.009$ | 118 | 0.78 | 13.59 |
| MgII  | $-0.153 \pm 0.029$ | $0.194 \pm 0.013$ | 124 | 0.79 | 14.31 |
| MgII  | $-0.095 \pm 0.018$ | $0.112 \pm 0.008$ | 124 | 0.77 | 13.23 |
| Fe5270 | $0.049 \pm 0.008$ | $0.015 \pm 0.004$ | 125 | 0.37 | 4.49 |
| Fe5555 | $0.029 \pm 0.009$ | $0.020 \pm 0.004$ | 125 | 0.33 | 3.84 |
| Fe5406 | $0.034 \pm 0.009$ | $0.018 \pm 0.004$ | 124 | 0.33 | 3.91 |
| Fe5709 | $0.054 \pm 0.008$ | $-0.004 \pm 0.004$ | 121 | $-0.17$ | $-1.88$ |
| NaD   | $-0.202 \pm 0.022$ | $0.157 \pm 0.010$ | 125 | 0.83 | 16.34 |

| High density |
|---------------|
| $H\beta$ | $0.173 \pm 0.013$ | $-0.036 \pm 0.006$ | 121 | $-0.50$ | $-7.75$ |
| Fe5015 | $0.063 \pm 0.010$ | $0.011 \pm 0.004$ | 125 | 0.21 | 2.46 |
| MgI   | $-0.185 \pm 0.020$ | $0.131 \pm 0.009$ | 118 | 0.78 | 13.59 |
| MgII  | $-0.153 \pm 0.029$ | $0.194 \pm 0.013$ | 124 | 0.79 | 14.31 |
| MgII  | $-0.095 \pm 0.018$ | $0.112 \pm 0.008$ | 124 | 0.77 | 13.23 |
| Fe5270 | $0.054 \pm 0.008$ | $0.015 \pm 0.004$ | 125 | 0.37 | 4.49 |
| Fe5555 | $0.039 \pm 0.009$ | $0.020 \pm 0.004$ | 125 | 0.33 | 3.84 |
| Fe5406 | $0.034 \pm 0.009$ | $0.018 \pm 0.004$ | 124 | 0.33 | 3.91 |
| Fe5709 | $0.054 \pm 0.008$ | $-0.004 \pm 0.004$ | 121 | $-0.17$ | $-1.88$ |
| NaD   | $-0.202 \pm 0.022$ | $0.157 \pm 0.010$ | 125 | 0.83 | 16.34 |

Figure 13. Comparison between $MgII$ index measured by Wegner et al. (2003) and our results (O08).

Figure 14. Number of companions ($N_c$) for the galaxies of our sample versus the radial velocity $v_r$. The concentration of galaxies around $v_r$ 1000 km s$^{-1}$ is related to the Virgo cluster.
Figure 15. Frequency distribution of the number of companions ($N_c$) according to morphological type, E (continuous line), and S0 (dashed line). Two galaxies in clusters of different richness, NGC 1399 in Fornax and NGC 4486 in Virgo, indicate the sensitivity of the $N_c$ determination method to distinct density regimes.

Figure 16. Frequency distribution of mass estimators for E (continuous line) and S0 (dotted lines).

From this figure, taking into account the coefficient errors, the metallic indices do not differ by more than 1.5σ. Interestingly, the most discrepant index is the NaD line, whose behavior may be caused by the influence of the more conspicuous interstellar medium expected for the lenticulars. This can also be seen on the slightly higher Hβ′ values for low-mass S0, indicating that this gas reservoir can be used to fuel star formation.

Similarly, we examine the possible influence of the environment on the relations defined above, using the definitions of Section 6.1, classifying galaxies in regions of low, medium, and high density of objects (LD, MD, and HD). Figure 21 shows the results and the parameters for the fits are listed in Table 12. As can be seen, there are no significant differences between metallic $I' - \log \sigma_0$ relations for LD and HD environments, in agreement with several previous works, except for Hβ′. Galaxies in LD environments display a steeper relation than those in HD, possibly indicating that the latter have, on average, older stellar populations. Furthermore, a less steep relation in high-density regions, is an indication of a truncated star-formation history at the low-mass end. Possible mechanisms responsible for this could be harassment (Moore et al. 1998) or gas stripping (Gunn & Gott 1972), both of which keep the morphology intact.

A comparison of our results with those available in the literature for nearby samples is shown in Figure 22, where we plot the coefficients computed in different environments. This
Figure 19. Index–log $\sigma_0$ relations for E (red dots) and S0 (blue dots) galaxies. The ordinary least-squares linear fits to the data are shown as continuous lines with the same colors as the related dots. Mean error bars are indicated in the upper left corner of each panel and indices are expressed in magnitudes.

is done despite the distinct selection criteria of each work, their reduction and analysis procedures, and density estimator. In the comparison we include the following authors: (1) Bernardi et al. (1998) who analyzed the Mg$_2$ index for field, group and cluster galaxies; their linear fits for each environment are very similar, thus we show only their cluster fit; (2) Kuntschner (2000) who analyzed data for 11 E and 11 S0 galaxies of the Fornax cluster, considered here equivalent to our HD definition; (3) Kuntschner et al. (2001) who analyzed 72 galaxies in groups and clusters; (4) Denicoló et al. (2005) who analyzed results for 84 galaxies with indices measured at $r_c/8$, distributed in the field and in groups, including 8 isolated galaxies; (5) Sánchez-Blázquez et al. (2006) who analyzed $I'$–log $\sigma_0$ relations for a sample of 98 objects divided in two environments defined by low (field, group, and the Virgo cluster) and high galaxy density (central region of the Coma cluster).

Figure 22 shows that, within the uncertainties, our $I'$–log $\sigma_0$ relations do not depend on environment. This is in agreement with the findings of Bernardi et al. (1998) and Denicoló et al. (2005). In contrast, Sánchez-Blázquez et al. (2006) reported a significant difference, and attributed it to a variation of chemical abundance ratios. These conflicting results may originate from the $\sigma_0$ ranges considered by the authors, sometimes by the sparse sampling of low $\sigma_0$ objects, by poor spectral resolution, or by the methodology in obtaining and analyzing the data.

We also compare our results with deeper samples. For instance, Bernardi et al. (2003b) find no dependence of the Mg$_2$–$\sigma_0$ and H$\beta'$–$\sigma_0$ relations on environment using the SDSS data. By contrast, Clemens et al. (2006) using data from the same survey, report “small, but very significant trends with environments.” A potential problem with analyses based on the SDSS is the adopted morphological classification, which is based exclusively on color properties. That may lead to a mixture of populations, including bulges of early spirals, which may follow different star-formation histories (Trager 2004). Since they reside in low-density regions, this may introduce a false dependence on environment.

The weaker correlation of Fe indices with velocity dispersion, as compared to those for $\alpha$ representatives (Mg) and the anti-correlation of H$\beta'$, which is not very sensitive to $\alpha$/Fe ratio (Korn et al. 2005), suggests a variation of the $\alpha$/Fe ratio with $\sigma_0$. This abundance ratio is associated with a short star-formation
history (Trager et al. 2000a; Thomas et al. 2005), which taken together with their inferred old luminosity-weighted ages and metal-rich content, are conflicting with the predictions from hierarchical clustering models and give support to the so-called downsizing scenario (Cowie et al. 1996), as observed by recent works (e.g., Denicol´e et al. 2005; Thomas et al. 2005; S´anchez-Bl´azquez et al. 2006). Theoretical efforts to explain these apparent inconsistencies are based on the use of AGN feedback to regulate the star-formation history (Scannapieco et al. 2005; De Lucia et al. 2006), also separating the stellar population birth time from the galaxy mass assembly time (De Lucia et al. 2006). Nevertheless, while no specific abundance ratio prediction is made, forming the bulk of stars before mass assembly leads to subsequent “dry-mergers,” currently a popular scenario for the origin of bright E galaxies (Bernardi et al. 2007).

Regarding the scatter of the $I'$–log $\sigma_0$ relation, although relatively small, specially in the case of the Mg 2 line, it cannot be explained solely by the uncertainties. As we have seen, the $\alpha$/Fe ratio and age also contribute to the slope of this relation, and one might wonder if the scatter can also be driven by age, a usual claim in the literature (e.g., Terlevich & Forbes 2002; S´anchez-Bl´azquez et al. 2006), or by variations of abundance ratios (e.g., S´anchez-Bl´azquez et al. 2006).

Following the discussion made by S´anchez-Bl´azquez et al. (2006), we tested for possible age effects on the scatter of the different $I'$–log $\sigma_0$ relations by measuring the correlation of the residuals ($\delta I'$) of the least-squares fits to the relations versus the H$\beta'$ index, which is an age-sensitive indicator. Plots of the $\delta I'$–H$\beta'$ relations are shown in Figure 23 for the sample divided by morphology, while the correlation parameters are listed in Table 13 which contains the results of the Spearman and $t$ tests. Apparently, there is no dependence of the scatter correlation on morphology (Table 13). The lines that show a significant anti-correlation of the residuals with H$\beta'$ are those of Mg and NaD$'$.

In contrast, the Fe (except for Fe5015) residuals do not show any dependence on H$\beta'$. The fact that the scatter of distinct

| Index   | S0         | E          |
|---------|------------|------------|
|         | $r_s$      | $t$        | $r_s$      | $t$        |
| Fe5015  | 0.166      | 2.566      | 0.322      | 5.105      |
| Mg1     | −0.252     | −3.843     | −0.241     | −3.723     |
| Mg2     | −0.258     | −4.089     | −0.183     | −2.812     |
| Mg$b$   | −0.258     | −4.082     | −0.285     | −4.505     |
| Fe5270  | −0.019     | −0.296     | 0.157      | 2.395      |
| Fe5335  | −0.070     | −1.068     | 0.087      | 1.321      |
| Fe5406  | 0.044      | 0.672      | −0.006     | −0.089     |
| Fe5709  | −0.007     | −0.107     | 0.099      | 1.487      |
| NaD     | −0.137     | −2.117     | −0.189     | −2.915     |
metallic lines behaves differently with Hβ' suggests that not only age has an effect on the scatter of the I'−log σ relation, but it may also be affected by the [α/Fe] ratio as suggested by Sánchez-Blázquez et al. (2006). The Fe5015' index, according to the line-formation calculations of Korn et al. (2005), is more sensitive to the chemical abundances of Ti and Mg than to that of Fe, where, in fact, Fe5015' anti-correlates with the abundance of Mg, what could explains its odd behavior amidst the Fe lines.

The results of the δI'−Hβ' relations according to the environments are shown in Figure 24 and in Table 14. The Mg and Na indices, which follow the α elements, give distinct answers, but Mg indices still tend to anti-correlate, while the NaD' index shows no correlation at all, a result that is shared by the Fe indices. In general, we find that those correlations do not vary significantly between LD and HD environments, except for the Fe5015' and the Mg b index. Similar analysis was carried out by Sánchez-Blázquez et al. (2006), who also found that Mg and Fe lines scatter with Hβ' behave differently, attributing it to α/Fe variations. However, they find that the residuals of Fe lines with Hβ' correlate in LD regions, but not in HD ones. On the other hand, Kuntschner et al. (2002) compared the scatter of the Mgb−σ relation in low-density regions and the Fornax cluster and found no difference between those environments. We also note that the scatter increases for galaxies with large Hβ', which are the low-mass objects. This result points toward the scenario
of downsizing (Cowie et al. 1996), where low-mass galaxies have an extended star-formation history.

7. SUMMARY

In this work we present the measurements of velocity dispersion and Lick indices obtained from high S/N (>20), long-slit spectra for 509 early-type galaxies, drawn from the ENEAR survey (da Costa et al. 2000), considered a fair representation of the present-day early-type population, having fairly similar distributions of apparent magnitude, radial velocity, morphology, and velocity dispersion to the ENEAR sample as a whole. This sample is one of the largest of its kind currently available in the nearby universe (z < 0.002), and complements the much larger and higher redshift (z > 0.005) data from the SDSS (Bernardi et al. 2003a; Clemens et al. 2006). While the latter has a large number of objects which is unmatched for statistical studies, it suffers from the uncertainties of color-based morphological classification, the limitations inherited to fiber-based measurements, and the need for spectra stacking, given the typical low S/N.

We find that our measurements of velocity dispersion and line strength indices are, in general, in good agreement with those available in the literature. A few discrepant cases exist, but these vary from line to line and from author to author, showing no systematic behavior. These data are used in this and forthcoming papers to study the chemical evolution of early-type galaxies. In the present paper we use different line indices-velocity dispersion relations to probe the properties of early-type galaxies. The relatively large sample allows us to split it, both by morphological types and different galaxy density regimes, without compromising the statistical significance of the sub-samples considered. We emphasize that our densities are estimated locally; therefore more representative than the broad categories such as field/groups/clusters normally used in some studies.

The main findings of this paper are as follows.

1. Our new measurements of velocity dispersion and Mg\textsubscript{2} are robust, agreeing with those obtained by Wegner et al. (2003) using a different methodology.
2. Our indices' measurements show small offsets when compared to those of other authors (Trager et al. 1998, 2000a; Wegner et al. 2003; Denicoló et al. 2005; Sánchez-Blázquez et al. 2006), but with comparable scatter, consistent with the error estimates. Furthermore, several more subtle effects such as the placement of the slit, the aperture size and the calibration procedure adopted may affect the measurements.
3. Independent of the mass estimator used we find that E galaxies in high-density regimes are on average more massive than those located in low-density regions. This
is in agreement with the conclusions of Clemens et al. (2006). In addition, we find that Es are more massive than S0 galaxies, a fact that has been used as an argument in favor of the hierarchical growth of elliptical galaxies.

4. As well known, we find that all the Mg indices show a relatively strong increase with $\sigma_0$ while the Fe indices depend only slightly on it. These correlations are interpreted by many authors (e.g., Bernardi et al. 1998) as driven mainly by metallicity in a coeval population, while others believe that age also plays an important role in defining this relation and its scatter (Trager et al. 2000a; Sánchez-Blázquez et al. 2006).

5. The observed distinct dependence of Mg and Fe on velocity dispersion, along with the anti-correlation with velocity dispersion of the H$\beta'$ index, which has a low sensitivity to the $\alpha$/Fe ratio, suggests that the chemical abundance ratio of Mg/Fe also varies with mass, as pointed out by several authors (e.g., Trager et al. 2000a; Kuntschner et al. 2002; Thomas et al. 2005; Sánchez-Blázquez et al. 2006).

6. In general, the metallic $I'$--$\sigma_0$ relations show no dependence on morphology or local density of galaxies. The exception is the NaD', where the low-mass lenticulars show stronger line indices than ellipticals with comparable $\sigma_0$. The H$\beta'$--$\sigma_0$ also shows a weak dependence on both morphology and local density. This result contrasts with the findings of Sánchez-Blázquez et al. (2006), based on a considerably smaller sample, and claims by Clemens et al. (2006) using the SDSS data.

7. The H$\beta'$ index decreases with $\sigma_0$ which suggests, along with the metallic lines, that the last episode of star formation for massive galaxies took place early in the galaxies' history. Comparing this relation in high- and low-density regions, we find that the slope of the relation is significantly flatter in high-density regions indicating that the star formation of low-mass galaxies has been interrupted by some interaction-like harassment (Moore et al. 1998) or gas stripping (Gunn & Gott 1972).

8. The residuals of Mg--$\sigma_0$ relation show correlation with H$\beta'$, decreasing for larger values of H$\beta'$. This dependence may indicate that variations in age contribute to the amplitude of the scatter of the Mg--$\sigma_0$ relation, especially in the case of low-mass objects. No such correlation is seen for Fe, which may be a hint for Mg/Fe variation taking part in the scatter.

The fact that massive galaxies have on average high values of Mg, low values of H$\beta'$, and relatively high Mg/Fe ratio, can be interpreted as evidence that massive elliptical galaxies are metal-rich and that the last burst of star formation was brief and
Figure 24. Residuals of index–log $\sigma_0$ relation versus H$\beta'$ for galaxies in LD (blue dots) and HD (red dots) environments. Related fits are also shown as continuous lines. MD points were omitted for clarity, but its fit is shown as a green line. In the upper right corner we display the mean error bar.

took place in an early phase of their history. The data also show that low-mass early-type galaxies are younger, metal poorer, and have an extended star-formation history, except those in high-density regions, where their star formation has been truncated, probably due to interactions with the intracluster medium. Taken together, this evidence favors the currently popular downsizing model for the formation of early-type galaxies.

It should be pointed out that interpreting the relations between metallic indices and $\sigma_0$ as a mass–metallicity relation for a population of coeval objects is not strictly correct and will be explored in a future paper, where we use evolutionary synthesis models to take into account the effects of age and abundance ratios (R.L.C. Ogando et al. 2008a, in preparation).

Finally, as demonstrated in Ogando et al. (2005), an alternative way to constraint models for the formation of early-type galaxies is to use the dependence of metallicity with the galactocentric radius, since the existence of steep gradients indicate a quick formation, as expected in monolithic-like models. In a forthcoming paper (R.L.C. Ogando et al. 2008b, in preparation), we use high-quality data for a sub-sample of the galaxies presented here to measure these gradients, extending our previous work.

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