ASTRONOMY
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The ESO-Sculptor Survey: spectral classification of galaxies with $z \lesssim 0.5^\star$

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Abstract. Using the ESO-Sculptor galaxy redshift survey data (ESS), we have extensively tested the Principal Components Analysis (PCA) method to perform the spectral classification of galaxies with $z \lesssim 0.5$. This method allows us to classify all galaxies in an *ordered* and *continuous* spectral sequence, which is strongly correlated with the morphological type. The PCA allows to quantify the systematic physical properties of the galaxies in the sample, like the different stellar contributions to the observed light as well as the stellar formation history. We also examine the influence of the emission lines, and the signal-to-noise ratio of the data. This analysis shows that the emission lines play a significant role in the spectral classification, by tracing the activity and abnormal spectral features of the observed sample. The PCA also provides a powerful tool to filter the noise which is carried by the ESS spectra.

By comparison of the ESS PCA spectral sequence with that for a selected sample of Kennicutt galaxies (Kennicutt 1992a,b), we find that the ESS sample contains 26% of E/S0, 71% of Sabc and 3% of Sm/Irr. The type fractions for the ESS show no significant changes in the redshift interval $z \sim 0.1 - 0.5$, and are comparable to those found in other galaxy surveys at intermediate redshift. The PCA can be used independently from any set of synthetic templates, providing a completely objective and unsupervised method to classify spectra. We compare the classification of the ESS sample given by the PCA, with a χ^2 test between the ESS sample and galaxy templates from Kennicutt (Kennicutt 1992a), and obtain results in good agreement. The PCA results are also in agreement with the visual morphological classification carried out for the 35 brightest galaxies in the survey.

Key words: galaxies: evolution – galaxies: fundamental parameters – surveys – galaxies: stellar content – methods: data analysis – methods: statistical

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1. Introduction

The classification of the galaxies in a 3-D galaxy map provides invaluable information for studying the formation and evolution of galaxies in relation to the large-scale structure. With these goals in mind, we have performed a spectral classification for the ESO-Sculptor Faint Galaxy Redshift Survey (ESS, hereafter; de Lapparent et al. 1993). The photometric catalogue of the ESS is based on CCD imaging and provides the B, V and R(Johnson-Cousins) photometry of ~ 13000 galaxies (Arnouts et al. 1997). The spectroscopic catalogue provides the flux-calibrated spectra of a complete sub-sample of ~ 700 galaxies with $R_c \leq 20.5$ obtained by multi-slit spectroscopy (Bellanger et al. 1995). The ESS allows for the first time to map in detail the large-scale clustering at $z \lesssim 0.5$ (Bellanger & de Lapparent 1995).

Morphological classification (Hubble 1936, de Vaucouleurs & de Vaucouleurs 1961, Sandage 1975), is based on the recognition of image patterns and it naturally started with the investigation of the nearest galaxies. For non-local galaxies, producing an *objective* morphological classification in the same classification system as for local galaxies is extremely difficult and would require a very complex taxonomy (Ripley 1993). The major limitation is the angular resolution given by ground-based telescopes. Only a rough classification can be made, for example by fitting de Vaucouleurs or exponential profiles or using the relationship between the central concentration index and the mean surface brightness (Doi et al. 1993). Moreover, this method can only be applied up to modest redshifts ($z \sim 0.2$). Recently, with the refurbished Hubble Space Telescope (HST), can one see the detailed morphology of galaxies up to $z \sim 0.7$ (or I $\lesssim 25$) (Abraham et al. 1994) and derive an acceptable morphological description up to $z \sim 3.0$ (van den Bergh 1997). Galaxies at these very high redshifts present a wide variety of morphologies, when compared to the nearby galaxies. However, when high redshift galaxies ($z \gtrsim 2.0$) are observed through visual photometric filters (*e.g.,* the HST filters), the morphology is delineated by the redshifted blue or the UV emission due to young stars or by star-forming regions, making the objects appear of later morphological types than they really are. This effect could

partially explain the high rate of distorted galaxies in the Hubble Deep Field (HDF) (van den Bergh 1997). In summary, the existing morphological classifications are severely dependent on the image spatial resolution, on the photometric filter, and as a result, on the redshift of the objects.

In contrast to the qualitative approach of the morphological classification, the principal physical characteristics of galaxies can be efficiently quantified by their spectral energy distributions (SED). For a given galaxy, the SED measures the relative contribution of the most representative stellar populations and constrains the gas content and average metallicity. It is therefore sensible to classify galaxies along a spectral sequence rather than a morphological sequence. Morgan & Mayall (1957) have shown that indeed there is a fundamental relationship between spectra of galaxies and their morphologies: three different populations which in general constitute every galaxy −the gas and the young and old stars (Bershady 1993, 1995)− contribute both to delineate the main morphological features (bulge, spirals arms, etc...), and the spectral features (the continuum shape, the emission lines and absorption bands). The spectral classification has several advantages over the morphological classification. The spectral range covered by low resolution spectroscopy (R $\sim$ 500) is wider than the standard filters, and thus allows to define a common interval for objects describing a wide range of redshifts. Furthermore, spectra are easier to handle than 2-D images when a large amount of data is processed.

In this paper we perform the spectral classification of the galaxies in the ESS, using the Principal Component Analysis (PCA). The PCA technique has been applied to many problems of variate nature, from social to biological sciences. In astronomy, it is frequently used for compressing data to extract the variables which are truly correlated (Bijaoui 1974; Faber 1973; Efstathiou & Fall 1984). The PCA has already been used to study inherent relationships between some selected features or quantities calculated from the spectra of Seyfert galaxies (equivalent widths and line ratios) and their photometric magnitudes (Dultzin-Hacyan & Ruano 1996), and on QSO spectra (Francis et al. 1992). In a recent study, Connolly et al. (1995) have tested the PCA using the spectral and morphological templates of Kinney et al. (1996), to show how the spectral properties and the Hubble sequence are related. Using Kennicutt spectra (Kennicutt 1992a), Folkes et al. (1996) and Sodre & Cuevas (1997), show the correlation between spectral properties and morphological type for normal galaxies.

Here we further test the PCA technique as a tool to achieve a reliable spectral classification for a new sample of distant galaxies. The PCA method is shown to be a powerful tool for measuring both, the systematic *and* non-systematic spectral properties of a galaxy sample. We also study the behavior of the PCA with respect to the data noise level.

The paper is organized as follows. In Sect. 2 we describe the ESO-Sculptor (ESS) spectroscopic data. In Sect. 3 a brief overview of the PCA technique and its application to the spectral classification are given, as well as the classification procedure using the χ^2 test. In Sect. 4 we apply the PCA to a sample of normal Kennicutt galaxies, and illustrate some specific features

Table 1. Characteristics of the ESO-Sculptor spectroscopic survey.

Center	$\alpha(J2000) \sim 0^h 20^m$
	$\delta(J2000) \sim -30°$
Sky coverage	$(\alpha)\ 1.3° \times (\delta)\ 0.27°$
b^{II}	$\sim -83°$
Magnitude limit	$R_c = 20.5$
Effective depth	$z \sim 0.5$
Telescopes used	ESO 3.6m and 3.5m NTT
Instruments	EFOSC (3.6m) and EMMI (NTT)
	with multi-object spectroscopy
Wavelength coverage	$\sim$ 4300-7000 Å (3.6m)
	$\sim$ 3500-9000 Å (NTT)
Total # galaxies	669
Spectral resolution	$\sim$ 20 Å (3.6m), $\sim$ 10 Å (NTT)
Slit width	$1.3 - 1.8$ arcsec
Redshift error	$\sim 100 - 150$ km sec^{-1}

of the method. In Sect. 5 the PCA is applied to the ESS. The analysis and the spectral classification are described in Sect. 6, along with the visual classification for the brightest galaxies. In Sect. 7 we compare our main results with those of other studies. The conclusions and prospects are summarized in Sect. 8.

2. The data

Table 1 above lists the main parameters and characteristics of the spectroscopic sample of the ESS (see de Lapparent et al. 1997). The redshifts are measured by cross-correlation (using the method developed by Tonry & Davis 1979) with galaxy templates which have been tested for the reliability of the redshift scale which they provide (Bellanger et al. 1995). For the $\sim$ 55% of galaxies with emission lines, an "emission redshift" is also measured by fitting the detected lines (mostly [OII], Hβ, and [OIII] at 4958 Å and 5007 Å). When the absorption and emission redshift agree, a weighted average is derived. The mean errors in the redshifts are given in Table 1. Detailed information on the acquisition and redshift measurements are described in Bellanger et al. (1995). The present spectral analysis is based on the subsample of 347 spectra having R(Cousins) $\leq$ 20.5, S/N $\geq$ 5, a reliable redshift measurement, and a spectrophotometric quality (see below). The remaining data to bring the redshift survey to completion are in the course of reduction. The only bias affecting the sub-sample used here is the tendency to observe the brightest galaxies in the R filter (see Fig. 14). There is no intended bias related to morphological type in the observing procedure. The full ESS spectroscopic sample is defined by only one criterion: $R_c \leq 20.5$ (R_c is an estimate of aperture magnitudes in the R Cousins filter, using the Kron estimator (Arnouts et al. 1997).

Because spectral classification techniques are sensitive to the continuum shape of the spectra, the flux-calibration is a crucial step which we now describe. This stage amounts to the calculation of the instrumental response curve, which depends on the telescope, instrument, and CCD combination, and is modulated by the variations in the transparency conditions at the moment of observation. We denote "calibrating curve"
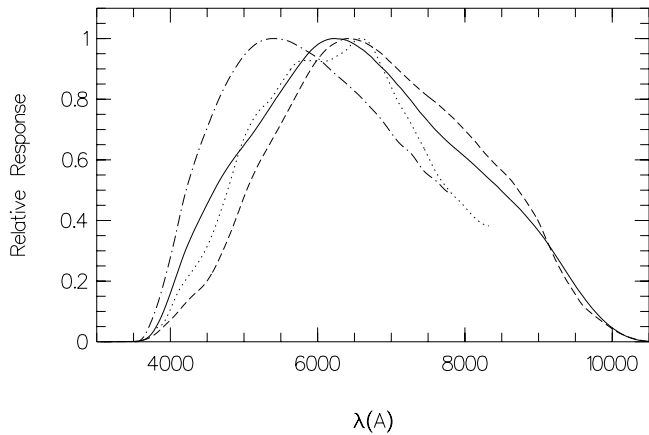
Fig. 1. Different "calibrating curves" (CC), corresponding to different instrumental set-ups. Solid and dashed curves represent typical CCs for the NTT telescope, and dotted and dot-dashed curves represent CCs for the 3.6m telescope.

the product of these two independent functions. The calibrating curves for some of the different instrumental set-ups used for the observations of the ESS are shown in Fig. 1. The instrumental response for each instrument is calculated from the observation of spectro-photometric standard stars and is the average ratio between the *observed* spectrum of the star and the *reference* spectrum, in good spectro-photometric conditions. For the ESS sample we used the standard stars LTT 377, LTT 7987 and Feige 21 (see Hamuy et al. 1992). Several standards (2-3) were observed each night or one standard was observed several times per night (2 to 3 times). The resulting r.m.s. variations in the calibrating curves during a night reported as photometric by the observer, and from one such night to another, are $\lesssim$ 10%. We therefore select from the available ESS spectroscopic sample all spectra obtained during these "stable" nights. We then correct each spectrum by the mean calibrating curve derived for the corresponding observing run. The resulting flux calibrations are only relative. An absolute calibration could be obtained using the photometric magnitudes (cf. Arnouts et al. 1997), but this is not necessary for the present analysis. The final subsample, which contains 347 spectra, represents 52% of the total of 669 galaxies with $R_c \leq 20.5$ (see Sect. 6.5 for completeness correction). Before the spectral analysis, the atmospheric O_2 absorption bands of the spectra, near 6900 Å and 7600 Å , are eliminated by linear interpolation from the surrounding continuum.

To assess quantitatively the spectro-photometric quality of the selected sample of 347 spectro-photometric calibrated spectra, two tests are performed: (1) the comparison of the spectra of the same galaxy, observed twice or more, and (2), the comparison of the photometric colors with the synthetic spectro-photometric colors. First, we found that 40 galaxies from the available spectral sample have 2 measured spectra. The r.m.s. variations in the ratios of the spectra for each pair are $\sim$ 7-10% when both are obtained in spectro-photometric conditions, and

$\gtrsim$ 10% when at least one spectrum of the pair is taken during a non-spectro-photometric night. This confirms that the spectro-photometric stability indicated by multiple observations of standard stars during each night is a reliable indicator of the spectro-photometric quality of the resulting calibrated spectra. Second, we calculate synthetic colors from the calibrated spectra, and compare the results with the standard colors obtained from the CCD photometric catalogue (see Arnouts et al. 1997). The photometric magnitude system is B(Johnson), V(Johnson), and R(Cousins). We compare colors rather than magnitudes in order to cancel out the unknown absolute flux calibration. We then fit a polynomial of degree 1 to the spectro-photometric versus photometric colors, for B−V and B−R. The slope is 0.952 ± 0.07 and 0.905 ± 0.08 for B−V and B−R, respectively (see Fig. 2). For a perfect correspondence, the slope should be 1.0. The dispersion around the fit are $\sigma[(B-V)_{spec}-(B-V)_{phot}] = 0.17$, and $\sigma[(B-R)_{spec}-(B-R)_{phot}] = 0.19$. These values are consistent with the dispersion resulting from the intrinsic photometric and spectrophotometric errors, which is $\sim \sqrt{2(0.04)^2 + 2(0.10)^2}$ ~ 0.15, where 0.04 and 0.10 are the intrinsic errors of the photometric and spectro-photometric data, respectively. Therefore, there is a good agreement between the spectro-photometric and photometric B−V and B−R colors for spectra taken during photometric nights, and our estimate of $\sim$ 10% for the external uncertainty in our relative flux calibrations appears valid.

We examine one last effect which could bias our flux-calibrated spectra. The 1-D spectra are obtained from the 2-D spectra using the optimal extraction weight method (Robertson 1986). This method weights differently the wings and the central parts of the light distribution in such a way that the noisier parts of the spectrum (the outer regions of the galaxy) have a smaller weight than the high S/N part of the spectrum (the core of the object). Typically, the weight in the wings is 12 to 20% of the weight in the center. Due to well known color gradients in the surface photometry of individual galaxies, the extracted spectra can be affected differently for different wavelengths, in such a way that the extracted spectra are dominated by the stellar content of the center of the light distribution. However, comparison of the spectra obtained using the weighted and the un-weighted extraction for 27 objects, shows that the optimal extraction method does not change the *shape* of the spectra by more than 3% (for spectra with S/N $\gtrsim$ 12). This is well inside the 10% spectro-photometric uncertainty in our flux-calibrated spectra.

3. PCA and χ^2 test: the formalism

A detailed description of the PCA technique can be found in Murtagh & Heck (1987), and in Kendall (1980). Here we summarize its main characteristics. The PCA is applied to a data set of N vectors with M coordinates. In this M-dimensional space, each object is a point and the sample forms a cloud of points. The central problem which is solved by the PCA is the description of the cloud of points by a set of P vectors of a new orthonormal base, with $P \ll Min\{N,M\}$ and with a minimal Euclidean distance from *each* point to the axes defined
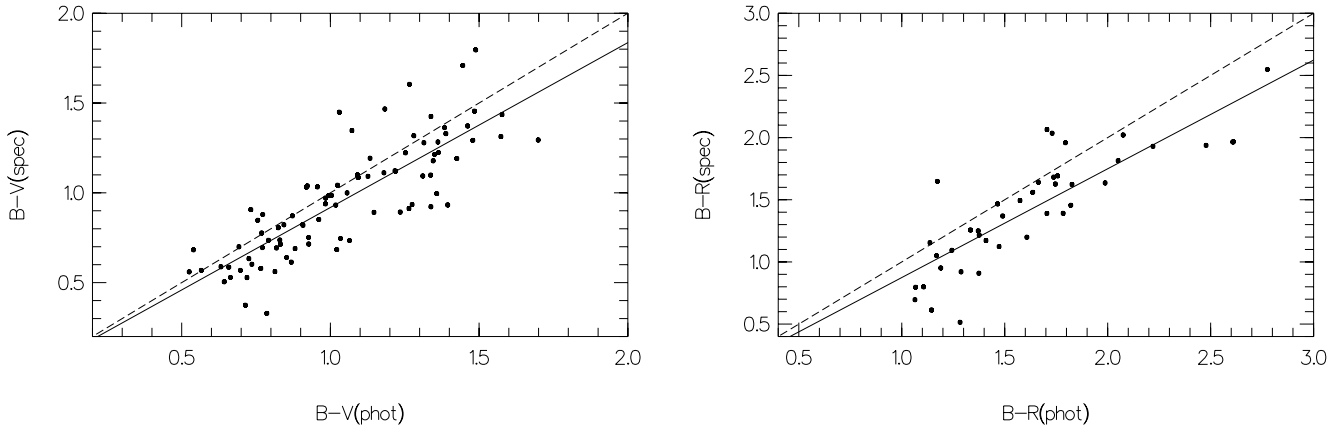
Fig. 2. Relationship between the photometric and spectro-photometric colors B−V and B−R. The parameters for the best linear fits (solid lines) are given in the text. The dashed lines indicate the locus for an hypothetical perfect correspondence (B–V)$_{spec}$ = (B–V)$_{phot}$, and (B–R)$_{spec}$ = (B–R)$_{phot}$.

by the new base. The eigenvectors of this new base are called principal components (PC). Minimizing the sum of distances between spectra and axes is equivalent to maximizing the sum of squared projections onto axes, *i.e.,* maximizing the variance of the spectra when projected onto these new axes.

The input for the PCA is a matrix of N spectra $\times M$ variables, which in our case are spectral elements with 2 to 10 Å/pix, depending on the resolution of the data. Each spectrum **S** is normalized by its norm (the square root of its scalar product with itself), yielding the N normalized spectra $\mathbf{S}^{norm}$ which serve as input to the PCA:

$$\mathbf{S}^{norm} = \frac{\mathbf{S}}{\sqrt{\sum_{j=1}^{Nbins} \mathbf{S}_j^2}}. \tag{1}$$

Other normalizations can be used (for example a flux normalization), but it was shown by Connolly et al. (1995) that the details of the normalization applied to the input $N \times M$ matrix do not have a strong influence onto the PCA results. However, the interpretation of the principal components does depend on the technique used to reduce the input matrix. Because our input vectors are normalized by their norm, we can apply the PCA onto the sum of squares and cross product (intermediate) matrix (SSCP method), which does not rescale the data nor center the data cloud. The normalized spectra then lie on the surface of a M-dimensional hyper-sphere of radius 1, and the first PC has the same direction as the average spectrum, but with norm equal to 1. Two other procedures are based on the variance-covariance matrix (VC method) and the correlation matrix (C method), respectively. The VC method places the new origin onto the centroid of the sample and the C method also re-scales the data in such a way that the distance between variables is directly proportional to the correlation between them. For the VC method the average spectrum has to be used in order to reconstruct individual spectra. We emphasize that neither the PC's nor the projections given by the SSCP method, used in this paper, are the same as those given by the VC method. However, if the

normalized cloud of points is concentrated in a small portion of the hyper-sphere, then the first PC of the VC method will have almost the same direction as the second PC given by the SSCP method (see Francis et al. 1992, Folkes et al. 1996). Although these different methods give different PC's, if we take into account the underlying transformations explained above, the physical interpretation of the PC's and the projections does not change, and the final result always satisfies the maximization conditions and the orthonormality among the different principal components.

After application of the PCA using the SSCP method, we can write each spectrum $\mathbf{S}^{norm}$ as

$$\mathbf{S}_{approx} = \sum_{k=1}^{N_{pc}} \alpha_k \mathbf{E}_k, \tag{2}$$

where $\mathbf{S}_{approx}$ is the reconstructed spectrum of $\mathbf{S}^{norm}$, α_k is the projection of spectrum $\mathbf{S}^{norm}$ onto the eigenspectrum $\mathbf{E}_k$ and N_{pc} is the number of PC's taken into account for the reconstruction. In Eq. (2), the PC's are in decreasing order of their contribution to the total variance.

We show in Sect. 5 below, that if the S/N is high enough (*i.e.,* $\gtrsim 8$), then we can take $N_{pc} = 3$ or 4 to reconstruct ~ 97 to 98% of the signal, respectively. If the S/N $\lesssim 8$, it requires a higher number of PC's to reproduce the initial spectrum to such high accuracy because of the noise pattern. Therefore, the first 2 or 3 components carry most of the signal in each spectrum, which leads us to use α_1, α_2 and α_3 to describe the spectral sequence. We choose to reduce these 3 parameters to the radius r and the angles δ and θ defined by the spectrum $\alpha_1 \mathbf{E}_1 + \alpha_2 \mathbf{E}_2 + \alpha_3 \mathbf{E}_3$ (as in Connolly et al. 1995) in spherical coordinates (δ the azimuth and θ the polar angle taken from the equator),

$$\alpha_1 = r \cos\theta \cos\delta \tag{3a}$$
$$\alpha_2 = r \cos\theta \sin\delta \tag{3b}$$
$$\alpha_3 = r \sin\theta. \tag{3c}$$

We express the values of δ and θ *independently* of the value of r:

$$\delta = \arctan\left(\frac{\alpha_2}{\alpha_1}\right) \tag{4a}$$

$$\theta = \arctan\left\{\left(\frac{\alpha_3}{\alpha_2}\right) \sin\left[\arctan\left(\frac{\alpha_2}{\alpha_1}\right)\right]\right\}. \tag{4b}$$

Note that we prefer the use of δ and θ (rather than the ratios α_2/α_1 and α_3/α_2) for defining the spectral sequence because they have a geometrical meaning. In the next section, we show that the physical meaning of δ is the relative contribution of the red (or early) and the blue (or late) stellar populations within a galaxy. Note that if $r \sim 1$, then from Eq. (3c), Eq. (4b) approximates to $\theta \approx \arcsin\alpha_3$.

For comparison with the PCA, we have implemented a simple χ^2 test between the galaxies of the ESS sample and a set of templates derived from the Kennicutt sample (Kennicutt 1992a, see Sect. 5 and Sect. 6). In contrast to the PCA, the χ^2 test is dependent on the set of templates used and can only provide a constrained classification procedure. The χ^2 between an observed spectrum and a template can be written as

$$\chi^2 = \sum_{j=1}^{N_{bins}} \frac{(\mathbf{S}_j - \mathbf{T}_j)^2}{\mathbf{S}_j + \mathbf{T}_j}, \tag{5}$$

where $\mathbf{S}_j$ and $\mathbf{T}_j$ are the values in the spectral element or bin j of the flux-calibrated spectrum and the template, respectively. N_{bins} is the total number of wavelength bins for both the spectrum and the template (we take the largest wavelength interval common to the spectrum and template, and rebin both to a common wavelength step of 5 Å/pix). The denominator measures the variance of the spectrum and the template, assuming that the noise is Poissonian. Because for a given observed spectrum N_{bins} is the same for all the comparison templates, the χ^2 value does not need to be normalized. Therefore, if we have a set of P templates, then the closest template k to the spectrum $\mathbf{S}$ is the one which satisfies

$$\chi^2_{\mathbf{T}_k} = Min\left(\chi^2|\mathbf{T}_1, \mathbf{T}_2, ..., \mathbf{T}_P\right). \tag{6}$$

Note that in the PCA treatment, the wavelength interval of all input spectra must be identical. For the χ^2 test, the wavelength interval can be larger than the one used for the PCA and varies from spectrum to spectrum. This difference will allow us to check the dependence of the PCA classification on the wavelength interval (cf. Sect. 6).

4. PCA and spectral sequence: test on Kennicutt galaxies

Connolly et al. (1995) have shown using the spectra from Kinney et al. (1996), that the first 2 projections of the PCA define a sequence tightly correlated with the morphological type. Folkes et al. (1996) and Sodre & Cuevas (1997) have demonstrated this property using a larger sample of spectra of local galaxies, namely the sample of Kennicutt (1992a). Here we use again the Kennicutt sample to complement the previous studies and to serve as comparison sample for the ESS sample. We have

Table 2. Kennicutt galaxies selected for PCA.

#	Galaxy	Type	#	Galaxy	Type
1	NGC3379	E0	15	NGC3627	Sb
2	NGC4472	E1/S0	16	NGC2276	Sc
3	NGC4648	E3	17	NGC4775	Sc
4	NGC4889	E4	18	NGC5248	Sbc
5	NGC3245	S0	19	NGC6217	SBbc
6	NGC3941	SB0/a	20	NGC2903	Sc
7	NGC4262	SB0	21	NGC4631	Sc
8	NGC5866	S0	22	NGC6181	Sc
9	NGC1357	Sa	23	NGC6643	Sc
10	NGC2775	Sa	24	NGC4449	Sm/Im
11	NGC3368	Sab	25	NGC4485	Sm/Im
12	NGC3623	Sa	26	NGC3227	Sb
13	NGC1832	SBb	27	MK270	S0
14	NGC3147	Sb			

selected 27 normal Kennicutt galaxies from Hubble types E0 to Im, by discarding peculiar morphological types, and excluding spectra of galaxies with a particular spatial sampling (strong HII regions or high extinction zones). Table 2 lists the ID, the names and morphological types of the selected galaxies. We apply the PCA to these spectra restricted to the spectral range 3700 to 6800 Å, with a pixel size of 5 Å, which is the highest possible resolution for that sample (see Kennicutt 1992a).

Left panel of Fig. 3 shows the angles δ and θ [see Eqs. (4a) and (4b)] for the 27 chosen Kennicutt spectra (see Table 2), showing the tight sequence strongly correlated with the morphological type, already shown by Sodre & Cuevas (1994), Connolly et al. (1995) and Folkes et al. (1996), using different coordinates.

With only the first 3 PC's, we can reconstruct, on average, 98% of the signal of each Kennicutt spectrum in Table 2. PC's of superior order do not contribute more than 2% to the signal. This was already demonstrated by Connolly et al. (1995), using the observed spectra of Kinney et al. (1996). The physical reason for this striking feature is closely related to the fact that the fundamental spectral features of normal galaxies can be described by a reduced number of stellar spectra, namely spectral types AV and M0III. This was first suggested by Aaronson (1978), using UVK color-color diagrams (see also Bershady 1993, 1995). To probe this effect using the PCA approach, we project stellar spectra (from Sviderkien 1988) of stars with types A0, A2, G0, and K0 of the main sequence, and two spectra corresponding to giants M0 and M1, onto the first 3 PC's from the Kennicutt sample and derive the values of δ and θ. Symbols other than points in the left panel of Fig. 3 show that the A stars and the M giants mark the extreme regions (or the extrapolation) of the Hubble sequence, whereas the G and K stars are located inside the sequence. In addition, the right panel of Fig. 3 shows the surprising similarity between the second PC of the Kennicutt sample (with the emission lines eliminated) and the second PC from the stellar spectral sample. This extends and further demonstrates the results of Aaronson (1978) and allows us to conclude that the spectra of nearby galaxies with normal Hubble types, may be described with a reduced number of stellar
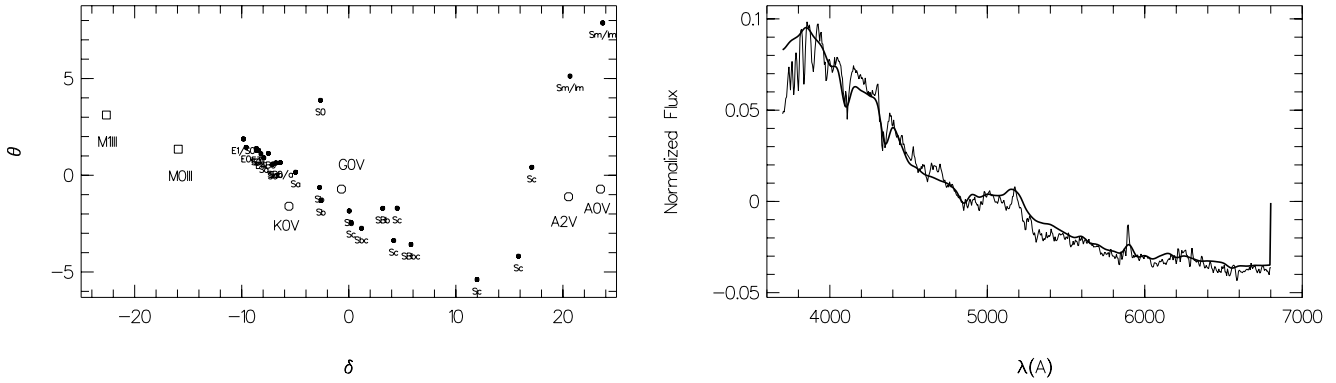
Fig. 3. The Kennicutt spectra of normal Hubble types (left figure, dots), onto the classification plane. Red or early type galaxies are to the left with $\delta \lesssim 0$ and blue or late types are to the right with $\delta \gtrsim 0$. The deviation in the θ parameter is mainly related to the emission lines. The circles and squares indicate the position of the spectra of main sequence stars and giant stars, respectively. The right panel shows a comparison between the second PC from the sample of Kennicutt normal galaxies (thin line) and the PC from the sample of stars appearing in the left panel (thick line).

spectra (2 types), at least in the spectral range which is considered here. Because the position of the observed galaxies along the δ axis accounts for the relative contributions of the red and blue stellar populations in the observed galaxies, we adopt the δ parameter to describe the spectral sequence.

As a complement, the parameter θ conveniently characterizes the presence of emission lines. The emission lines play an important role in the spectral classification of galaxies. They serve to characterize the strength of star formation, the nuclear activity and abundances, using for example the ratio between the strength of different emission lines. Francis et al. (1992), apply successfully the PCA technique to understand the systematic properties of QSO's. The role of θ is demonstrated by truncating the emission lines from all the Kennicutt spectra. This is done by fitting a polynomial of degree one to the adjacent continuum for each line. The resulting values of δ and θ are shown in Fig. 4. The ordering of the Hubble sequence along the δ axis remains the same as for the sample with emission lines. However, all spectra now have smaller $|\theta|$ values. Fig. 4 therefore shows that the emission lines increase the dispersion in the (δ,θ) plane, placing galaxies with strong emission lines far from the equator defined by $\theta = 0$. The known correlation between star formation and/or activity and the Hubble type for morphologically normal galaxies explains the observed correlation between θ and δ in Fig. 3.

Folkes et al. (1996) have studied in detail the reconstruction error as a function of the S/N in the input spectra, using simulated spectra constructed from the Kennicutt sample. They also demonstrated the greatly improved capability of the PCA for filtering the noise over other standard techniques. Here we also find that the noise in the input spectra has no effect onto the classification space (δ,θ) and that the observed δ sequence remains unchanged when adding arbitrarily high noise onto the Kennicutt spectra of Table 2: decreasing the S/N of the spectra down to 10% of their original value yields a change of $\frac{|\Delta\delta|}{|\delta|} \lesssim 7\%$ on the average (θ changes by $\Delta\theta \lesssim 0.1$ for galaxies without
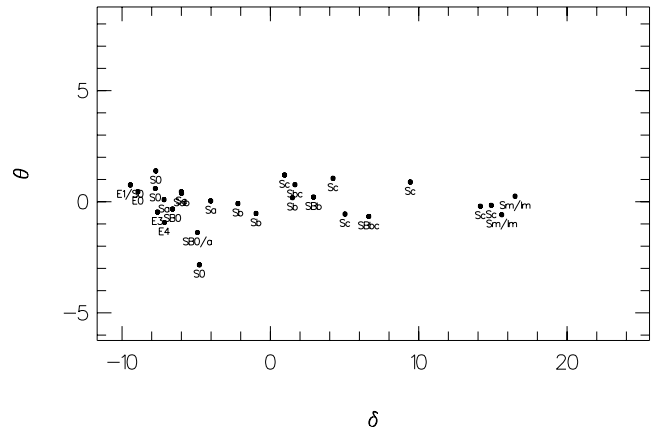

Fig. 4. The figure shows the Kennicutt templates with the emission lines removed, projected onto the spherical space (δ,θ), with the same scale as in Fig. 3.

emission lines, that is types E0 to Sa, with $|\theta| \lesssim 4°$; $\Delta\theta \sim 3$ for types Sc and Sm/Im, with $|\theta| \gtrsim 4°$).

5. PCA applied to the ESS sample

In this section we apply the PCA to the ESS sample of 347 flux-calibrated spectra described is Sect. 2. As the input spectra for the PCA must have identical wavelength intervals and number of bins, each spectrum is rebinned to rest frame wavelength with a step of 5 Å/pix which is small enough for not destroying spectral features and large enough for not introducing non-existent patterns in the signal. This step is slightly larger than the typical steps obtained with the 3.6m and the NTT, which are ~ 3.4 and 2.3 Å/pix, respectively (see Sect. 2). Because the spectra were obtained with multi-object spectroscopy, the wavelength coverage is not the same for all the spectra in the catalogue and is a function of the position of the slit along the dispersion direction on the aperture mask. In order to maximize the number of

Table 3. Minimum and maximum rest wavelengths defining samples 1, 2 and 3. Also shown is the number of galaxies in each sample.

Sample	λ_{min} (Å)	λ_{max} (Å)	N
1	3700	5250	277
2	3700	4500	33
3	4500	6000	27
other			10

spectra to be analyzed, one must carefully select the wavelength domain. Sample 1 defined in Table 3 provides a good compromise between a wide wavelength interval and a large number of spectra (80% of the total number of spectra analyzed). The wavelength interval contains major emission and absorption features usually present in galaxy spectra: [OII] (3727 Å), the H & K CaII lines (3933 and 3968 Å), CaI line (4227 Å), Hδ (4101 Å), the G band (4304 Å), Hβ (4863 Å), [OIII] (4958 Å and 5007 Å), and MgI (5175 Å). Samples 2 and 3, contain the "blue" and "red" spectra caused by extreme positions on the aperture masks (near the edges) sometimes combined accidentally with high or low redshift. The PCA is applied separately to samples 1, 2 and 3. For the 10 objects which do not belong to any of samples 1, 2 or 3, we only apply the χ^2 method described in Sect. 3. For application of the PCA to the 3 samples defined in Table 3, we normalize each spectrum by its norm as defined in Eq. (1) and we use the sum of squares and cross product matrix method for the PCA, described in Sect. 3.

The main PCA analysis of the ESS data is performed on sample 1. The redshift distribution for this sample has the same shape as for the full sample of 347 objects (a Kolmogorov-Smirnov test shows that the two distributions have a 78.2% probability to originate from the same parent distribution, with a confidence level of 87.7%). We are therefore not introducing a redshift bias when using sample 1. Fig. 5a shows the projections of the 277 spectra of sample 1 onto the first 2 PC's derived from that sample. The galaxy marked with an arrow is an extremely blue galaxy. Fig. 5b shows the projections after normalizing to the first 3 projections ($\sqrt{\alpha_1^2 + \alpha_2^2 + \alpha_3^2} = 1$). Although the normalization to the first 3 PC's artificially decreases the scatter in the (α_1,α_2) sequence, this normalization changes the position of the points in the (δ,θ) plane by a very small amount: $\frac{\Delta\delta}{\delta} \sim$ 0.0003 and $\frac{\Delta\theta}{\theta} \sim 0.002$ (see Fig. 5c).

Justification for adopting the $\sqrt{\alpha_1^2 + \alpha_2^2 + \alpha_3^2} = 1$ normalization comes from the high reconstruction level reached using the first 3 PC's, with $< \sqrt{\alpha_1^2 + \alpha_2^2 + \alpha_3^2} > \sim 98\%$ for sample 1. The distribution of errors we make with this approximation for sample 1 is shown in Fig. 6, where we plot the χ^2 value between the original and reconstructed spectra (using 3 PCs) and the error in the reconstruction defined as

$$PCA_{error} = 1 - \sqrt{\alpha_1^2 + \alpha_2^2 + \alpha_3^2}. \qquad (7)$$

It can be shown analytically that the following relation exists:

$$PCA_{error}(n) \simeq B + A\,\chi_n^2, \qquad (8)$$

with A, B constants ≥ 0. The label n denotes the spectrum n. The linear relation between PCA_{error} and χ^2 is clearly visible in Fig. 6. This result also confirms the reliability of the PCA reconstruction and associated error PCA_{error}.

Figs. 5a,b show that the spectral sequence for the ESS galaxies is similar to the sequence found by Connolly et al. (1995) for the 10 Kinney nearby galaxies. The spectral sequence of Fig. 5c is also similar to that shown in Fig. 3 (left), for the Kennicutt spectra (see Table 2). Note that we verified (as in Sect. 4) that the inclusion or rejection of the emission lines mainly affects the θ parameter, and therefore the presence of emission lines does not significantly affect the results of the spectral classification.

To compare the (δ,θ) sequence for sample 1 with that for the Kennicutt templates, we project the spectra of Table 2 onto the PC's obtained by the application of the PCA to sample 1 of the ESS (open circles in Fig. 5c). The normal Kennicutt galaxies lie along the sequence for sample 1, which shows that the ESS data describes the full Hubble sequence. We also notice in the ESS sample the existence of galaxies *redder* and *bluer* than the earliest and latest normal Kennicutt Hubble types, respectively. These and other cases will be discussed in Sect. 6. Application of the PCA to samples 2 and 3 yields a fairly well defined sequence in the (δ,θ) plane, similar to that for sample 1. However, the absence of the 4000 Å break within the wavelength interval for sample 3 yields a larger scatter in (δ,θ).

Fig. 7 shows the first 4 PC's obtained for sample 1 (bold lines). The first PC of sample 1 is characterized by the CaII K and H absorption lines near 4000 Å, a pronounced continuum break and by the other absorption features typical of early-type galaxies. The first 4 PC's also contain [OII], Hβ and both [OIII] emission lines. The projections onto the first 4 PC's for sample 1 satisfy $< |\alpha_1| > = 0.97$, $< |\alpha_2| > = 0.10$, $< |\alpha_3| > = 0.023$, $< |\alpha_4| > = 0.021$. In addition, $< |\alpha_5| > = 0.016$ and PC's of higher order contribute less than 1% of the total flux. Fig. 7 also shows the PC's derived by application of the PCA onto the Kennicutt spectra (thin lines), using a wavelength interval restricted to the same spectral range as for sample 1 (from $3700 \leq \lambda \leq 5250$ Å). The resemblance of the first 4 PC's for both samples is striking, which shows that the galaxy population in sample 1 has similar spectral properties to the sample of normal, local galaxies selected by Kennicutt. One must however be careful in comparing both samples, because the number of objects differ by a factor of ~ 10 and properties such as the blue and red continuum and the strength of emission lines in the first PC's depend on the frequency of the particular Hubble types. In this respect, although the selected Kennicutt spectra are representative of the spectral features observed in normal galaxies, the population fractions are *not* representative of the local universe. This could be responsible for the slight differences in the PC's between sample 1 and the Kennicutt sample: the 1st and the 2nd PC of the sample 1 are redder and bluer than the 1st and the 2nd PC's of the Kennicutt sample, respectively; and the strengths of the emission lines for the 4 PC's differ.

In conclusion, according to the PCA technique, the ESS galaxies with $z = 0.1 - 0.5$ have similar spectral properties in the range $\lambda = 3700 - 5250$ Å to the Kennicutt sample of
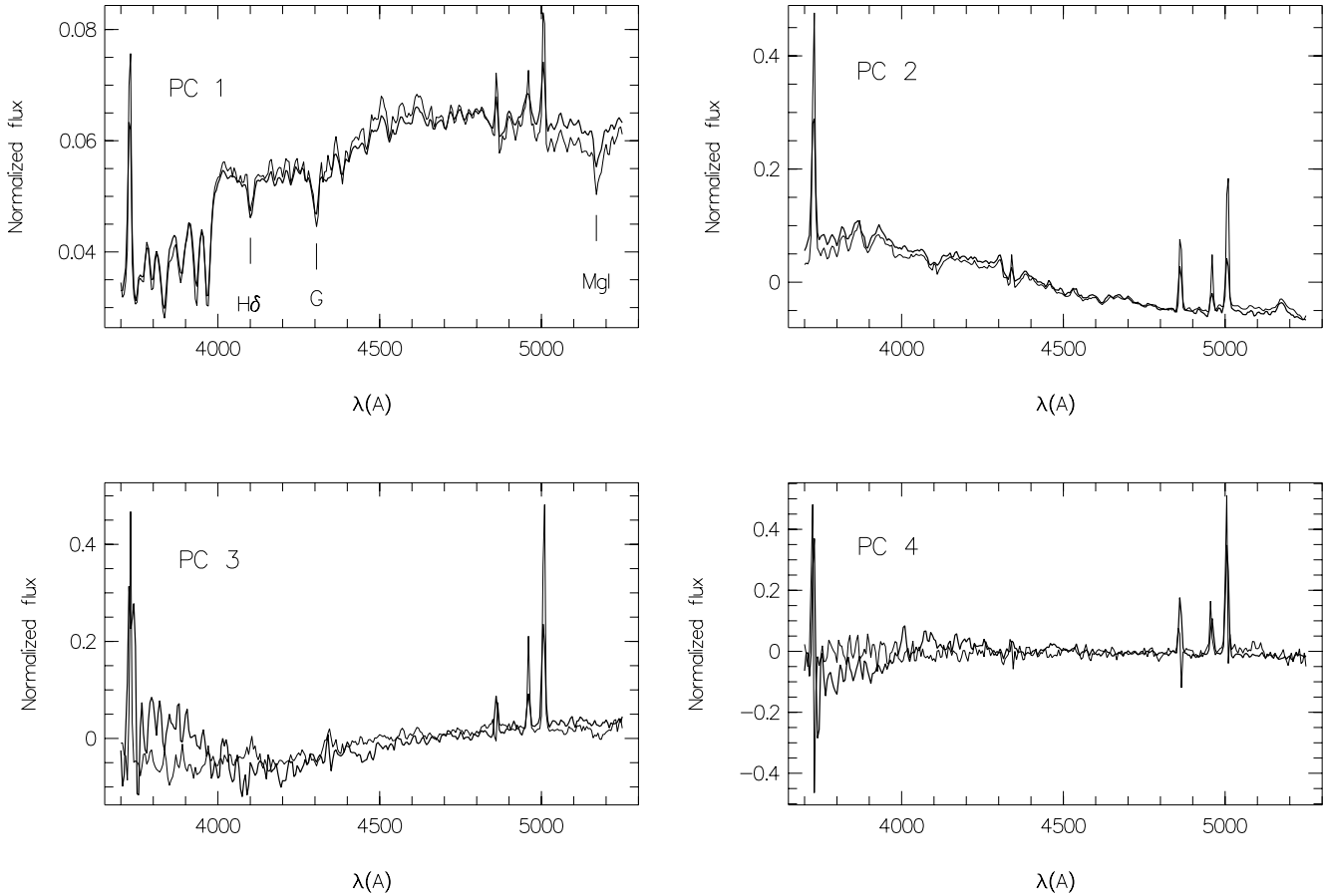
Fig. 7. First four eigenvectors for the PCA applied to sample 1 of the ESS (bold lines) and for the selected galaxy sample from Kennicutt (thin lines). The spectral range for both samples, when applying the PCA, is $3700 \leq \lambda \leq 5250$ Å.

galaxies with $z \lesssim 0.025$, which supports a close resemblance of the fractions of stellar populations between the two samples.

6. Analysis

6.1. Classifying the galaxies

In this paragraph we perform the spectral classification of the ESS galaxies, using the δ sequence. Our goal is not an indirect morphological classification using the spectral classification. The objective is to establish a link between the spectral classification and the known Hubble sequence in order (1) to test the reliability of the PCA classification by comparison with the χ^2 technique, and (2) to compare the ESS classification with that for other redshift surveys. The major assumption is that the spectral trends for the observed galaxies have the same nature as the spectral trends followed by the Kennicutt sequence, in which we know *a priori* the morphological type. In order to assign discrete types for comparison with the Hubble sequence, we define a type-δ relationship using the Kennicutt templates.

Fig. 8 shows the galaxies of sample 1 in the (δ,θ) plane (dots), and 6 galaxies of known Hubble type, which are the average of several of the Kennicutt templates from Table 2 with the

same type (open circles). The EL type is the average of galaxies # 1, 2, 3 and 4 of Table 2. The other types are S0 (average over objects # 5, 7 and 8), Sa (# 9, 10, and 12), Sb (# 14, 15 and 26), Sc (# 16, 17, 20, 21, 22, and 23) and Sm/Im (# 24 and 25). These average spectra are then projected onto the PC's derived from the ESS sample 1. The different averaged Kennicutt spectra in Fig. 8 are not equally separated in the (δ,θ) plane. It was already known that spiral galaxies have larger differences in their spectra than ellipticals (Morgan & Mayall 1957, Wyse 1993). Fig. 8 provides a quantitative demonstration of this effect: the change by one morphological type for early-type galaxies in the averaged Kennicutt galaxies, corresponds to a small variation in δ, compared to the late-types. In Fig. 8, the density of objects $\rho(\delta)$ is significantly higher for low values of δ than for high values of δ: ~ 15 gal/deg for $\delta \sim [-10, -2.5]$ and ~ 8 gal/deg for $\delta \sim [-2.5, 8.0]$. The large δ distances between the Sb and Sc and between the between the Sc and the Sm/Im leave space for the intermediate types Sbc, Scd, etc..., and for the Sd type, respectively, for which there are no templates in the Kennicutt's sample.

The observed position of the average Kennicutt templates along the δ axis, provides a natural binning for correlating the spectral sequence and the Hubble type, which we define by
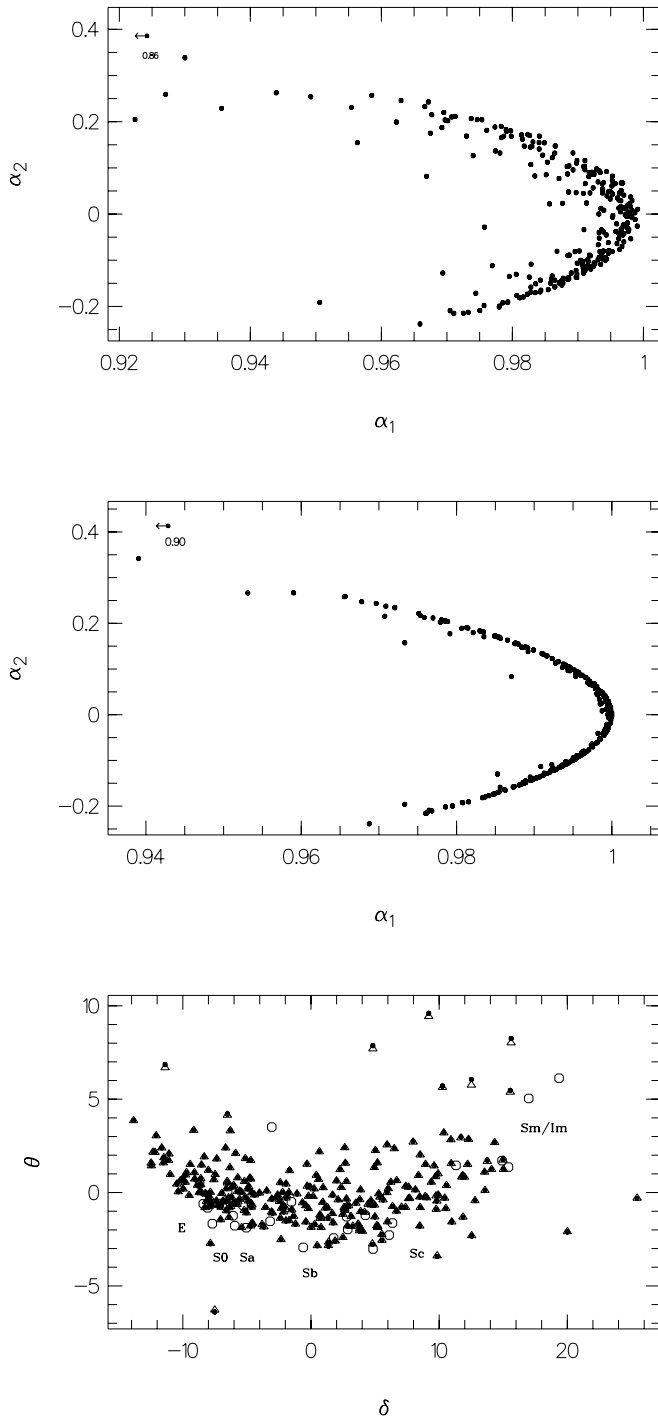
Fig. 6. The relationship between the error in the PCA [defined by Eq. (7)] and the χ^2 value between the input spectrum and its reconstruction using the first 3 PC's.

regions I, II, III, IV, V and VI, separated by vertical lines in Fig. 8. The boundaries of these regions are the averaged δ value between 2 adjacent average Kennicutt templates. This variable binning accounts for the *varying* density $\rho(\delta)$ which, as mentioned above, is inherent to the frequency of the spectral properties of the ESS galaxies. We also define a uniform binning in δ denoted I', II', III', IV', V', and VI'. The length for each bin in this case is the total span in δ divided by the number of morphological/spectral types. Table 4 shows the bin values in δ for the uniform and non-uniform binning. Also shown in Table 4 are the number of galaxies per bin and the corresponding fractions from the total of 310 galaxies for the combination of samples 1 and 2.

A bootstrap test shows that the r.m.s. deviation in the number of galaxies within each class in Table 4 is ~ 2, that is 0.7% in the fractional number per type given in Table 4. The largest source of error comes from the uncertainties in the flux calibrations of the spectra. The 7% external errors in the calibrations curves induce a 5% error in the number of galaxies per spectral class. Using bootstrap experiments we also derive an r.m.s. deviation in δ of 0.22°, and an r.m.s. uncertainty in δ varying from 0.2° at $\delta = -10°$, to 2.3° at $\delta = 20°$.

Table 5 shows the results of the χ^2 (see Sect. 3) applied to the galaxies of samples 1, 2 and 3 (347 in total) with the 6 averaged Kennicutt galaxies as templates. Considering the discrete nature of the χ^2 method, it is important to establish an indicator of the error which we make in the association of a type. We define it as the fraction of total galaxies for each type for which the second closest template has a χ^2 value differing by less than 20% from the χ^2 with the closest template (column 3 of Table 5). We choose 20% as a conservative threshold: given the 7% uncertainty in the flux calibration, we consider that cumulative squared differences less than 20% between a spectrum and 2 templates is not significant. The histogram of Fig. 9 shows the corresponding distribution of galaxy types for the sum of samples 1, 2 and 3 using the χ^2 method (solid lines). The dotted and dashed lines represent the distributions of types derived

Fig. 5a–c. Uppermost two panels: **a** projections onto the first 2 eigenvectors for the spectra of sample 1 of the ESS (see text and Table 3). **b** same as upper panel, with normalization to the first 3 projections: $\sqrt{\alpha_1^2 + \alpha_2^2 + \alpha_3^2} = 1$. The arrow indicates an extremely blue galaxy. Bottom panel **c**: the 277 galaxies of sample 1 in the classification space (δ,θ) with normalization to the first 3 projections (open triangles) and without normalization(filled circles). Open circles map the projections of the 27 Kennicutt templates of Table 2 onto the first 3 PC's obtained from sample 1 and with the $\sqrt{\alpha_1^2 + \alpha_2^2 + \alpha_3^2} = 1$ normalization.
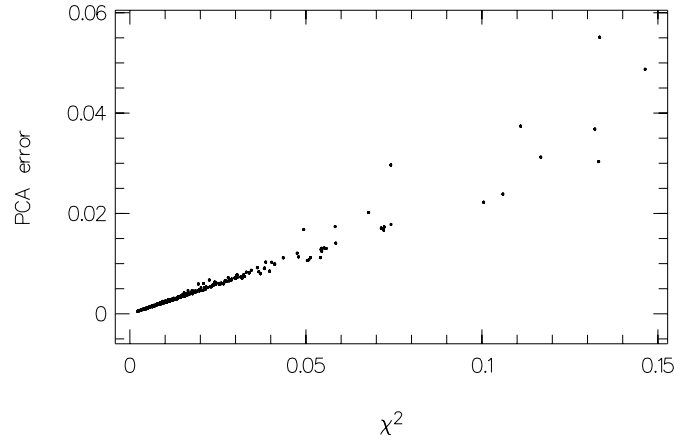
Table 4. PCA classification for samples 1 and 2. N(PCA) indicates the numbers and fractions of galaxies for the defined spectral types, using the position of the spectra along the δ axis (see Fig. 8). We show the results for uniform and variable bins in δ. The variable binning is obtained from the projected position of the averaged Kennicutt templates in Fig. 8 (see text).

Uniform Binning[a]			Variable Binning[a]			
Spectral Type	δ range	N(PCA)	Spectral Type	Kenn. Temp[b]	δ range	N(PCA)
I'	]$-14,-9$]	27(8%)	I	E	]$-\infty,-7.5$]	52(17%)
II'	]$-9,-4$]	91(29%)	II	S0	]$-7.5,-6$]	29(9%)
III'	]$-4,1$]	59(19%)	III	Sa	]$-6,-2.5$]	48(15%)
IV'	]$1,6$]	64(21%)	IV	Sb	]$-2.5,5$]	97(32%)
V'	]$6,11$]	46(15%)	V	Sc	]$5,14$]	75(24%)
VI'	]$11,16$]	23(7%)	VI	Sm/Im	]$14,\infty$[	9(3%)
I'-II'	]$-14,-4$]	118(38%)	I-II	E/S0	]$-\infty,-6$]	81(26%)
III'-V'	]$-4,1$]	170(55%)	III-V	Sa/Sb/Sc	]$-6,14$]	220(71%)

Notes:

[a] See Fig. 8 and explanations in the text.

[b] Kennicutt averaged templates used in the definition of the variable binning (see text).
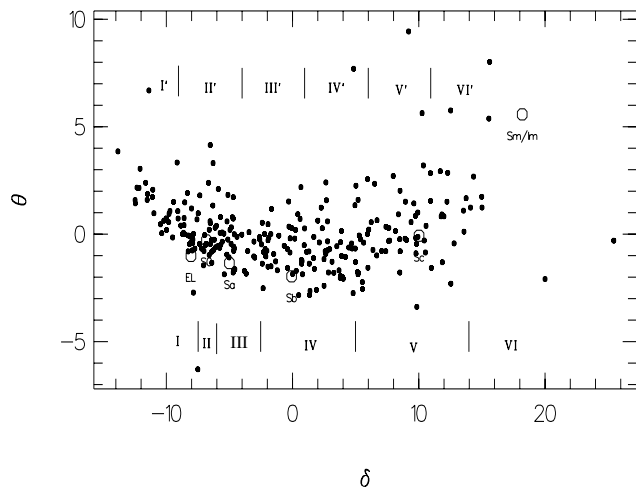

Fig. 8. Position of galaxies from sample 1 in the (δ,θ) plane (●), and of the 6 averaged Kennicutt templates (○) projected onto the PC's of sample 1. The spectral sequence is binned in two different ways: a variable binning in δ (marked as I, II, etc...) which follows the position of the Kennicutt templates, and a uniform binning in δ (marked as I', II', etc...). Vertical lines indicate the boundaries of the δ classes.

Table 5. Results of the χ^2 spectral classification method over samples 1, 2 and 3, using averaged Kennicutt templates described in the text.

Kenn. Temp.	N(χ^2)[a]	$\Delta_{\chi^2}^{(b)}$
E	33(10%)	5%
S0	50(14%)	8%
Sa	64(18%)	6%
Sb	107(31%)	0.8%
Sc	89(26%)	0%
Sm/Im	4(1%)	0%
E/S0	83(24%)	14%
Sa/Sb/Sc	260(75%)	7%

Notes:

[a] Number of galaxies per type, and percentage of the total of 347 galaxies.

[b] Fraction of galaxies, for each Hubble type, for which the χ^2 value between the first closest template and the second one is less than 20%.

from the PCA using the uniform and non-uniform binnings in δ, respectively, as defined in Table 4. The reader should recall that the χ^2 test is performed over the *whole* spectral range covered by each ESS spectrum, and therefore the comparison between the PCA and χ^2 method also provides a test of the influence of the spectral range on the spectral classification. For a uniform spanning of types in δ (dotted line) there are large differences with respect to the χ^2 method (solid line), for almost all types. On the other hand, the non-uniform binning based on the averaged Kennicutt templates (dashed line) gives a good agreement between the PCA and the χ^2 results, especially for late types, thus further demonstrating the reliability of the PCA technique in classifying galaxy spectral types. Note that the $\sqrt{\alpha_1^2 + \alpha_2^2 + \alpha_3^2} = 1$ normalization changes the type fractions given in Tables 4 and

5 by less than 0.1%. In Sect. 7.2 we compare the type fractions of Tables 4 and 5 with the results of other major surveys.

The fact that the χ^2 test over the whole sample of 347 galaxies, using the largest possible spectral range for each spectrum (see Table 2) produces nearly the same[1] fractions of spectral types (see Fig. 18) than the PCA over sample 1 restricted to the spectral range (3700-5250 Å), confirms that this spectral interval is wide enough for application of both techniques.

6.2. Filtering effect of the reconstruction and type dependence

We now illustrate the filtering capability of the PCA using the ESS sample. Fig. 10 shows the S/N of the reconstructed spectra of sample 1 using 3 PC's, as a function of the original S/N, for the different spectral types. The filtering effect of reconstructing the spectra with 3 PC's is striking. Whereas the S/N of the input spectra range from 6 to 40, the reconstructed spectra have S/N between 35 and 80. The gain in S/N is strongly dependent on the

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[1]   A Kolmogorov-Smirnov test shows that the probability that the values of column 7 of Table 4 and column 2 of Table 5 originate from the same parent distribution is 73.2% with a 85% of confidence level.
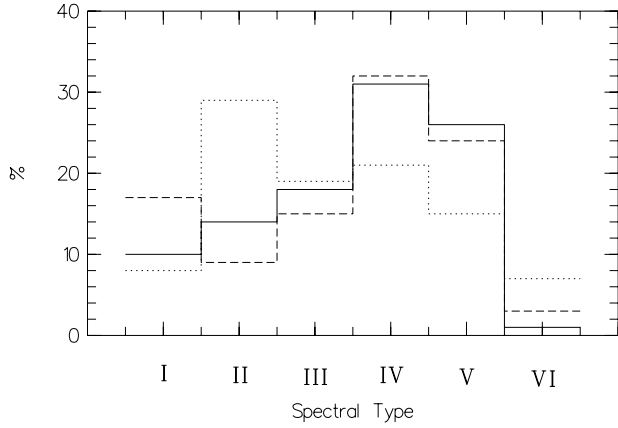
Fig. 9. Histogram showing the distribution of spectral types derived by the χ^2 method (solid line, over samples 1, 2 and 3) and the PCA (samples 1 and 2 included). Dashed and dotted lines indicate the results using a non-uniform and uniform binning in δ, respectively (see Tables 4 and 5).
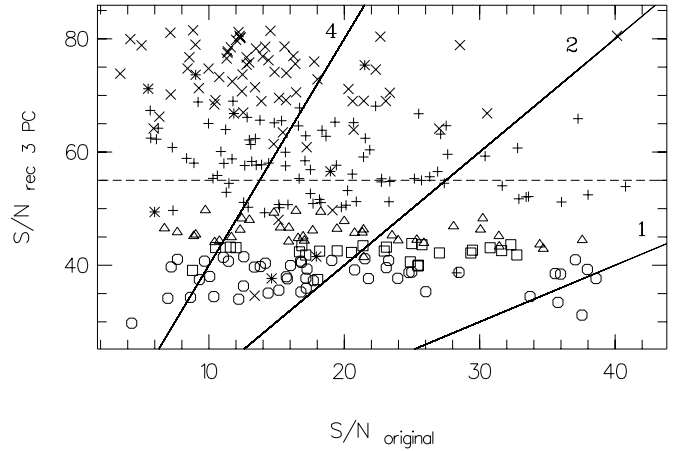

Fig. 10. S/N of the input spectra and their reconstructions using the first 3 PC's. The different symbols indicate spectral type: I($\circ$), II($\square$), III($\triangle$), IV(+), V($\times$), VI($*$). Lines indicate the boundary of a gain in S/N equal to factors of 4, 2 and no gain. The dashed line indicate the S/N of the first PC.
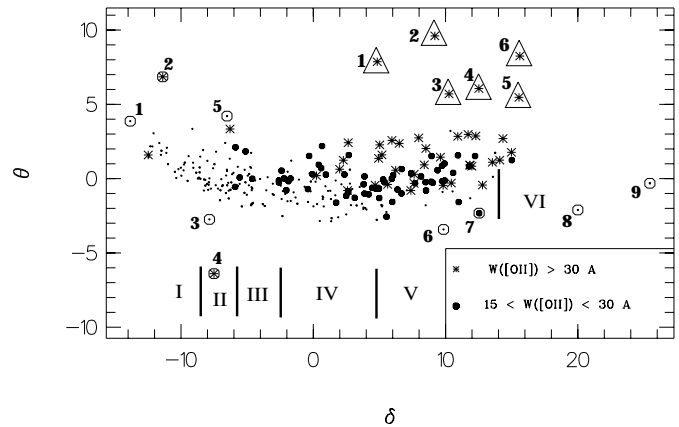
spectral type. For late types, the increase in S/N has the largest values, which reaches more than a factor of 4 for 70% of the types V and VI. This is due to the low S/N ratio in the weak continuum of the original spectra, which allows a relatively large improvement in S/N. For most of the early types (I to II), the gain in S/N is larger than 1.5 times, and can be as high as a factor 5. The range of variation for the S/N of the reconstructed spectra is related to the S/N of the PC's. The PC's have an intrinsic level of noise, and there is a minimum and maximum S/N achieved with the permitted linear combinations of the first 3 PC's for the defined spectral sequence. In Fig. 10, the dashed line indicates the S/N of the first PC (55).

We conclude that the noise carried by the original spectra can be reduced to an interval of well known S/N values, if one uses the reconstructed spectra. The S/N in the original spectra is a function of the apparent magnitude of the objects and the observing conditions, whereas the S/N in the reconstructed spectra depends only on the systematic and statistically significant spectral characteristics of the objects. Of course, in the limiting case when the noise is so high as to hide all the spectral features, the PCA error [Eq. (7)] is large. With data of sufficient S/N ratio, the possibility of reconstruction allows to transform the original sample of spectra into a sample with a reduced noise level. The filtered spectra can then be used for follow-up study of the various galaxy populations, and for comparison of the spectral features with models of spectro-photometric evolution. Note however that the details of the line properties, like equivalent width or line strength, are not linear and cannot be described in detail by the linear PCA approach.

6.3. The emission line galaxies

We now examine the properties of the [OII] emission line, present in $\sim$ 55% of the ESS spectra, in relation to the PCA classification. Fig. 11 shows the (δ,θ) values for the galaxies

Fig. 11. Galaxies of sample 1 (277 galaxies) with W([OII]) < 15 Å (dots), with 15 $\leq$W([OII])$\leq$ 30 Å (filled circles), and with W([OII])$\geq$30 Å (stars). Open circles indicate the peculiar galaxies discussed in Sect. 6.6, ordered following Table 8. Triangles denote emission line galaxies discussed in Sect. 6.3.

of sample 1, and indicates the points with measured equivalent widths (W, hereafter) of [OII] (3727 Å) satisfying W([OII]) $\geq$ 30 Å (asterisks), and 15 Å$\leq$ W([OII]) < 30 Å (filled dots).

In Fig. 11, most of the galaxies with $\delta \gtrsim 5°$ (types V/Sc and later), have W([OII]) $\geq$ 15 Å. There are only 4 galaxies with W([OII]) $\geq$ 30 Å and types I/E or II/S0. Table 6 shows the number and fraction of galaxies with 15 $\leq$ W([OII]) $\leq$ 30 Å and W([OII]) $\geq$ 30 Å for different spectral types. We give the mean redshift and the mean value of θ for each sub-sample and the corresponding standard deviations. Table 6 first displays the well known trend between the spectral type and the frequency of strong emission lines: the later the type, the larger the fraction with strong emission lines, and the stronger the emission lines. For a given spectral class (IV, V, VI), θ is systematically larger

Table 6. Information on the emission-line galaxies[a].

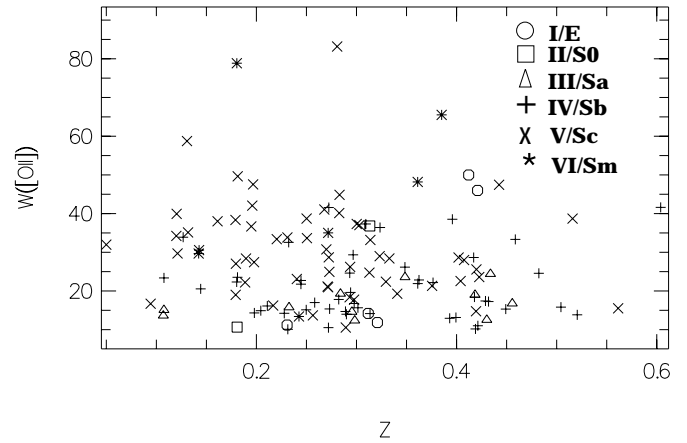| Spectral type[b]	N	Fraction	$\overline{z}$	σ_z	$\overline{\theta}$	σ_θ
		$15 \leq W([OII]) \leq 30$ Å				
I(E)	0	0%				
II(S0)	0	0%				
III(Sa)	7	18%	0.33	0.13	0.44	1.0
IV(Sb)	27	31%	0.32	0.10	−0.17	0.97
V-VI (Sc/Sm/Im)	29	38%	0.28	0.10	−0.044	1.0
		$W([OII]) \geq 30$ Å				
I(E)	3	6%	0.34	0.13	0.3	0.1
II(S0)	1	4%	0.31	0.0	3.3	0.0
III(Sa)	0	0%				
IV(Sb)	8	9%	0.34	0.14	1.6	2.7
V-VI (Sc/Sm/Im)	31	41%	0.23	0.10	2.2	2.5

Notes:
[a] For sample 1, 277 galaxies, 89% of the total number of galaxies analyzed.
[b] Using the non-uniform binning (see Table 4).

for galaxies with larger W([OII]) (see Table 6). This confirms the relationship between θ (*i.e.,* the power of the third eigen-vector for each spectrum), and the strength of emission lines. Fig. 12 shows that within each subsample of Table 6, the objects span most of the redshift range for the ESS ($0.1 \lesssim z \lesssim 0.5$).

The equivalent width of [OII] allows us to examine the possibility of galaxy evolution using the average value of W([OII]), as a function of redshift: W([OII]) is a direct measure of the degree of star formation in a galaxy (see for example Osterbrock (1989) and references therein), because this radiation is produced by the interstellar medium (ISM) which is excited by the ultraviolet (UV) radiation from hot stars. Several scenarios of galaxy evolution predict an increase in the star formation rate with increasing look back times. Observational evidence is provided by the excess of blue galaxies in deep number counts (Couch & Sharples 1987, Colless et al. 1993, Metcalfe et al. 1995 and references therein) as well as the increasing density of emission line galaxies in deep redshift surveys (Broadhurst et al. 1988). The Butcher-Oemler effect shows signs of recent evolution in clusters of galaxies (at $z \sim 0.2$) which can be partly interpreted in terms of increased star formation (Butcher & Oemler 1978, Dressler & Gunn 1983, Lavery & Henry 1988). One of the current issues is whether analogous effects occur in the field and at which redshift. Hammer et al. (1997) show that the fraction of bright emission-line galaxies in the field gradually increases with redshift, from 34% to 75% in the redshift range $0.45-0.85$. Their [OII] luminosity density of field galaxies increases only weakly from $z = 0$ to $z = 0.4$ (by a factor 1.6), and by a large factor (8.4) between $z = 0.4$ and $z = 0.85$. Similar results are found from other data samples, using different selection criteria and/or different spectroscopic techniques (Heyl et al. 1997). In the ESS sample analyzed here, we do not detect any significant evidence for an increase of W([OII]) with redshift up to $z \sim 0.5$ (see Fig. 15). This result agrees with those given by Hammer et al. (1997) and by Heyl et al. (1997).

Fig. 12. Equivalent widths of [OII] for galaxies with $W([OII]) \gtrsim 10$ Å, as a function of redshift and spectral type.

We also note the presence of [OII] in several early type galaxies of the ESS sample. In particular, there are 4 galaxies with types I-II/E-S0 which have W([OII]) > 30 Å (with $\delta < 0$ and marked with an asterisk in Fig. 11). The nature of this emission is not fully clear. However, some agreement exists (see for example Dorman 1997) to point out that very hot post-AGB stars present in such galaxies could be the source responsible for the [OII] emission, probably also related to the so-called Ultraviolet Upturn Phenomenon ("UVX"); NGC 1399 a well-known example of this effect (Dorman 1997). It also was suggested that the environment could play an important role in the "UVX" phenomenon (Ellis 1993). Note that 2 of 4 early-types galaxies with emission lines in the ESS sample belong to the same group of galaxies (at $z = 0.41$) and the other 2 have $z = 0.19$ and 0.31.

Fig. 13 shows the spectra of the six galaxies with $\delta \geq -4$ and $\theta \geq 5.0$ (open triangles in Fig. 11). They all have W([OII]) > 30 Å, and, except one, have spectral types later than IV/Sb. The spectra show clear signatures of strong star formation or activity. If we place these 6 emission-line galaxies onto diagnostic diagrams of $\log([OIII]\lambda 5007/H\beta)$ versus $\log([NII]\lambda 6584/H\alpha)$ or $\log([OIII]\lambda 5007/H\beta)$ versus $\log([SII]\lambda 6716+\lambda 6731/H\alpha)$ (Villeux & Osterbrock 1987), we find that galaxies # 1, 2, 5 and 6 are most likely HII galaxies (*i.e.* have a high current stellar formation rate). Only galaxy # 3 lies clearly inside the Seyfert 2 region. Galaxy # 4 was impossible to classify due the absence of Hα from the spectrum. Note that the ESS fraction of AGN ($\sim 2\%$) is in marked disagreement with the large fraction ($\sim 17\%$) found by Tresse et al. (1996) at $z \lesssim 0.3$ in the Canada France Redshift Survey (CFRS).

6.4. Redshift distribution and completeness

To the limiting magnitude $R_c = 20.5$, the spectroscopic sample used for the spectral classification in this paper (sample 1) represents 41% of the complete magnitude-limited sample. For a given magnitude bin, the inverse fraction of galaxies having a
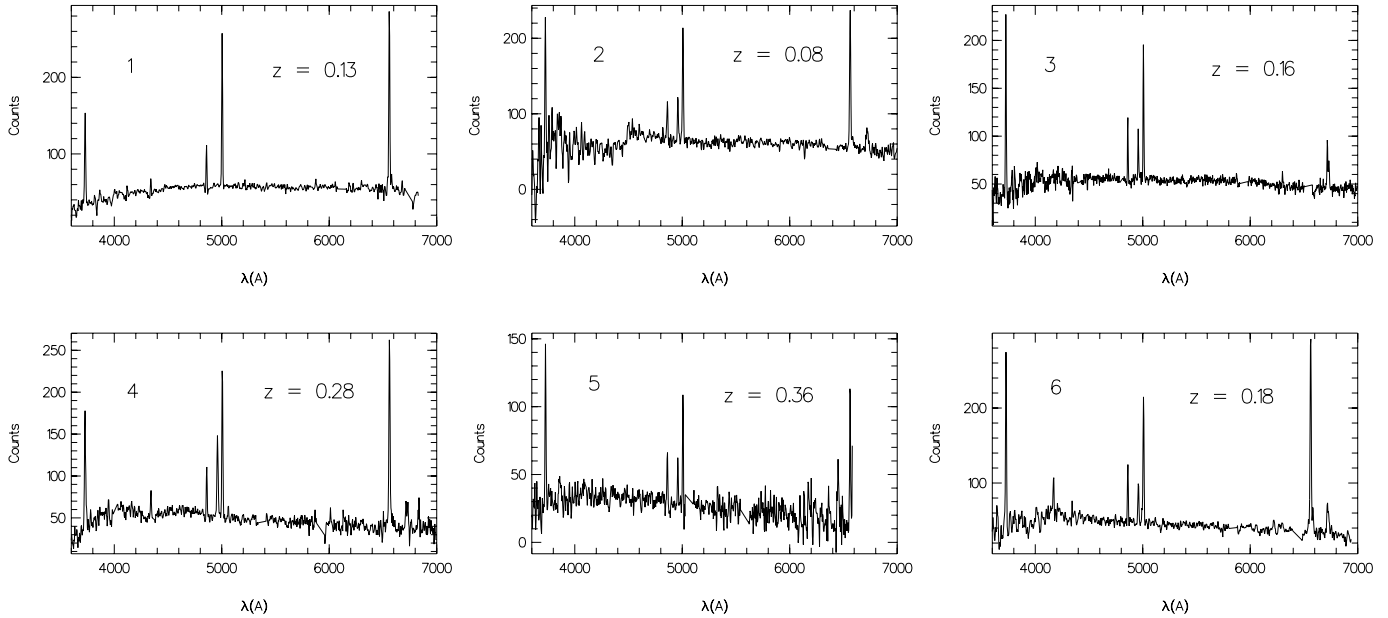
Fig. 13. Spectra of the galaxies in the ESS sample 1 (at rest-wavelength) with $\delta \gtrsim 4°$ and $\theta \geq 5°$. The galaxies are marked as open triangles in Fig. 11 and have W([OII]) $\geq$ 30 Å. For each object, the spectral type and W([OII]) in Å are: #1, IV/Sb, 52; #2, V/Sc, 44; #3, V/Sc, 38; #4, V/Sc, 50; #5, VI/Sm-Im, 46; #6, VI/Sm-Im, 51.

measured redshift gives the completeness correction to apply for that bin. Bottom panel of Fig. 14 shows the histogram of galaxies per 0.5 magnitude bin. The solid line represents the total number of galaxies in the ESS spectroscopic sample with $R_c \leq 20.5$ (669 galaxies). The dashed line represents the histogram of the 277 galaxies of sample 1 used in most of the analysis. Upper panel of Fig. 14 shows the completeness as a function of R_c magnitude for sample 1 (in 0.5 magnitude bins). We then correct the number of galaxies *per type* which are obtained in Sect. 6.1 and Table 4 by using the inverse of the completeness curve. The resulting type fractions are nearly identical for all spectral types, with absolute changes $\lesssim 1\%$ in the type fractions. The small variations result mainly from the homogeneous spread of different types as function of apparent magnitude.

Fig. 15 shows the distribution of types in redshift space (for $0.1 \leq z \leq 0.6$), using the PCA spectral classification. The type population is stable as a function of redshift for $z \lesssim 0.4$, with spectra of type IV(Sb) as the dominant type, followed by type V(Sc) with no clear indication of evolution in the type populations with z. Recall that the absolute errors in the population fractions are $\sim 5\%$ (note that the last bin has a small number of objects, so the errors in the population fractions are larger). Fig. 15 indicates however a significant excess in the fraction of early types at $z = 0.4 - 0.5$: the local density of galaxies with types I-II/E-S0 is 3.1σ above the average value for $z = 0.1 - 0.6$ (using $\sigma_{types} = 5\%$). This effect could be caused by the presence of an elliptical-rich group of galaxies. The complete redshift sample is necessary for further investigation of this feature.

6.5. Morphology-spectral relationship for the ESS sample

We now examine the morphology-spectral relationship for the ESS sample by testing whether our spectral classification procedure is consistent with the morphology of some of the objects. We have performed a visual morphological classification of the 35 brightest galaxies in samples 1 and 2. CCD images of these objects in the R filter (Arnouts et al. 1997) are given in Fig. 16, in decreasing order of brightness along with the orientation of the slit used to obtain the spectra. The redshift, R_c magnitude, morphological and PCA spectral types are listed in Table 7. These galaxies span the magnitude range R_c = 15.82-18.58 and the redshift range $z \sim 0.10$-0.25, with one galaxy having $z = 0.42$ (# 28). The morphological classification is inspired from that for the Revised Shapley Ames Catalog (Sandage & Tammann 1981). It was performed by GG in two steps. The first step was to make a rough classification based on the search for three features in each galaxy: disc and/or bulge and/or spiral arms. If a galaxy could not be included in any of these 3 categories, it was assigned a "peculiar" morphology. Note was taken of signs of merging or interaction when present. The second step was to define sub-classes within ellipticals (bulges with/without discs) and spirals (disc and/or spiral arms). This task is difficult (but not impossible!) because the objects are small ($9'' \lesssim D \lesssim 12''$). The discs are therefore poorly visible and the contrast of the spiral arms is weak. In Fig. 16, the spiral arms are clearly visible in object # 1, and discs are visible in # 17, 30, 31, etc... Careful visual inspection of the images of the galaxies using variable contrast allows to discover the presence of spiral arms in many cases. This can be done for $R_c \lesssim 18.0$ (objects # 1 to 17), for which the typical apparent
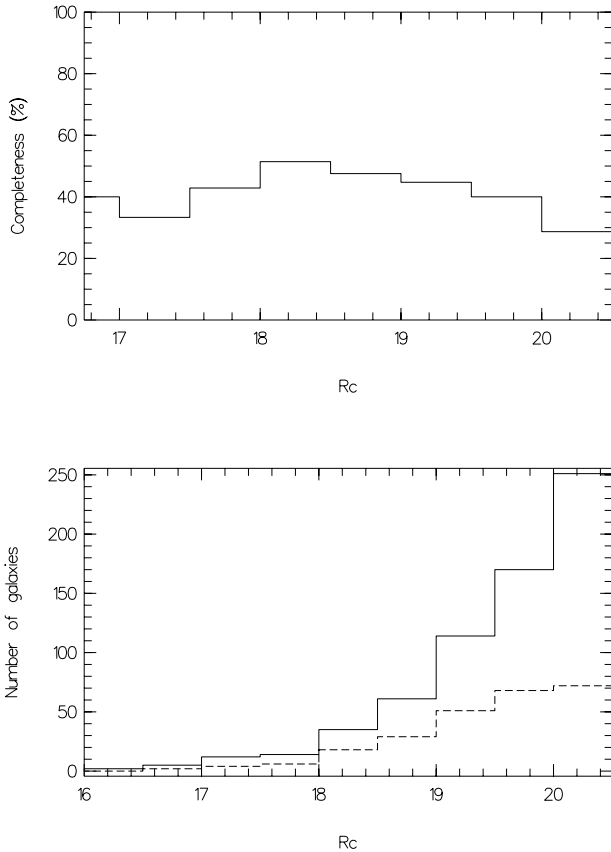
Fig. 15. Fraction of galaxies of each spectral type, per redshift interval. The spectral type is provided by the PCA over sample 1 (277 galaxies). The bin size is $\Delta z = 0.1$. The absolute 1σ errors in the type fractions are $\sim 5\%$ in $0.1 \lesssim z \lesssim 0.5$ and $\sim 15\%$ for $0.5 \lesssim z \lesssim 0.6$, this last value due to the reduced number of galaxies.

Fig. 14. Bottom panel: histograms showing the total number of galaxies per bin of 0.5 magnitudes and with $R_c \leq 20.5$ (total 669, solid), and the number of galaxies used for the present analysis (the 277 galaxies of sample 1, dashed). Upper panel: the fraction of the total number of galaxies per 0.5 magnitudes in R_c in sample 1.

Fig. 16. The 35 brightest galaxies (filter R_c) is the ESS sample listed in Table 7. The spatial extension of galaxy # 1 is $\sim 18''$ and it is $9'' - 12''$ for galaxies labeled # 2 to 38. ID number correspond to those in Table 7, where some galaxies have more than one spectroscopic measure (see also Fig. 17).

diameter of the galaxies is $\gtrsim 12''$. For fainter magnitudes, visual detection of the spiral arms is very difficult. We note that the spectral type of each galaxy was kept unknown prior to the morphological classification, in order to avoid a psychological bias. The morphological classification was repeated one month later after sorting at random the galaxies to be classified. In general, the second morphological type does not differ from the first assigned type by more than one morphological type (see Fig. 17).

Fig. 17 shows that there is good agreement between the visual morphological classification and the PCA spectral classification, for most of the selected galaxies. The mean difference between spectral and morphological type is ± 0.8 type, with an r.m.s. type dispersion of 0.5. We stress that the good agreement between spectral type and morphological type for the objects in Table 7 suggests that we have been successful in our visual classification in reproducing the typical morphological criteria used in the Kennicutt sample. This also suggests that the low redshift members of the ESS survey ($z \sim 0.1 - 0.25$) have a similar morphological-to-spectral relationship than the nearby galaxies ($z \sim 0$) in the Kennicutt sample. Note that the morphological classification of the Kennicutt *local* sample is done
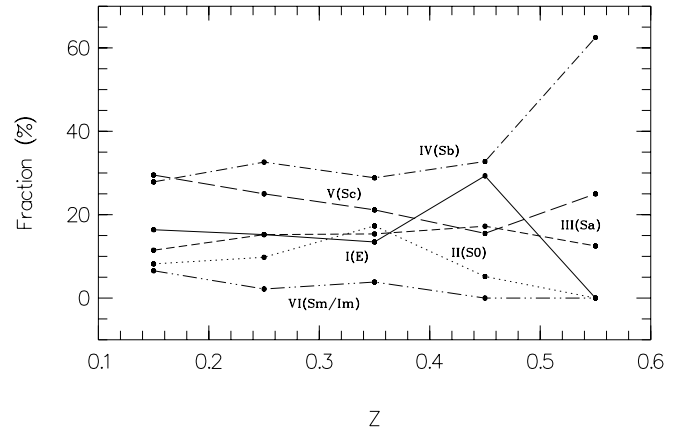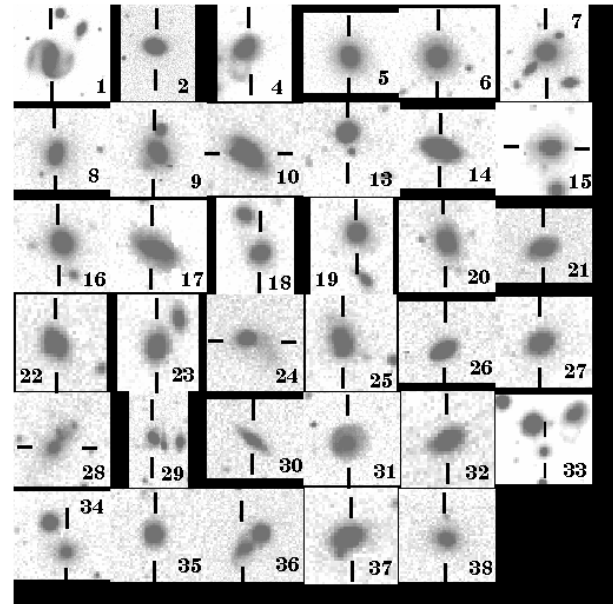
in the B band, and this is consistent with our classification being performed on the R images: the B filter "redshifts" to the R filter at $z \sim 0.21$ (the average redshift of the objects in Table 7).

6.6. Peculiar objects revealed by the PCA

One of the useful features of the PCA is its capability to detect objectively objects which deviate from the general trend. In Fig. 11, we mark with open circles galaxies which lie out-

Table 7. The redshift, R magnitude, visual morphological type and PCA spectral type for the 35 brightest galaxies (and their 38 spectra).

#	z	R_c	Morphological type	Spectral type (PCA)	Comments
1	0.11	15.82	SBb	III(Sa)	
2	0.12	16.62	S0/Sa	III(Sa)	
3	0.12	16.62		II(S0)	Same galaxy as 2
4	0.25	16.91		III(Sa)	M?
5	0.11	17.08	E/S0	I(E)	
6	0.16	17.12	E/S0	I(E)	
7	0.18	17.35	E/S0	II(S0)	
8	0.13	17.38	E/Sa	III(Sa)	D
9	0.19	17.56	S0/Sa	I(E)	D,M
10	0.23	17.68	Sa/Sb	III(Sa)	D
11	0.23	17.68		III(Sa)	Same galaxy as 10
12	0.23	17.68		IV(Sb)	Same galaxy as 10
13	0.19	17.74	E/S0	III(Sa)	G
14	0.18	17.80	S0/Sb	IV(Sb)	
15	0.23	17.82	E/Sa	II(S0)	VD
16	0.16	17.89	E/Sb	I(E)	VD
17	0.23	17.98	Sa/Sc	IV(Sb)	
18	0.22	18.03	E/S0	I(E)	M, VD
19	0.27	18.12	E/S0	III(Sa)	M, VD
20	0.18	18.19	S0/Sa	II(S0)	
21	0.18	18.20	Sa/Sc	IV(Sb)	
22	0.26	18.21	E/Sa	II(S0)	VD
23	0.22	18.22	E/Sa	I(E)	M, D
24	0.18	18.23	Sa/Sb	II(S0)	M, P
25	0.32	18.25		I(E)	M?
26	0.18	18.27	Sa/Sc	IV(Sb)	
27	0.23	18.33	E/S0	I(E)	D
28	0.42	18.33		I(E)	P, M, VD
29	0.19	18.34	Sa/Sb	IV(Sb)	
30	0.13	18.36	S0/Sb	I(E)	
31	0.17	18.39	S0/Sb	IV(Sb)	
32	0.19	18.40	S0/Sa	II(S0)	
33	0.26	18.42	E/S0	I(E)	D, M, G
34	0.23	18.43	E/S0	II(S0)	G
35	0.19	18.50	E/S0	I(E)	
36	0.28	18.50	E/S0	I(E)	M, VD
37	0.26	18.54	E/Sa	II(S0)	M
38	0.27	18.58	E/Sa	I(E)	

Notes:

P: Peculiar.
M: Merger.
G: Group.
D : Classification difficult.
VD: Classification very difficult.

side of the main (δ,θ) sequence and outside the sequence of emission-line galaxies (see Sect. 6.3) in order to show that the degree of peculiarity is related to the departure from the main sequence. Although galaxy #5 has a close neighbor in the (δ,θ) plane, we only show object # 5 because two spectra with δ values differing by less than 5% are indistinguishable. The spectra of the selected objects are shown in Fig. 18. Redshift, R_c magnitudes, colors, spectral and morphological types of these objects are listed in Table 8. Visual examination of the R CCD images of these objects has been performed. In general, the spectral and morphological type agree within the uncertainties in determining the morphology (see Sect. 6.6). It is interesting to note that the images of the six of nine galaxies show clear signs of peculiarities and/or merging. One galaxy even shows a jet-like feature (# 7). Galaxy # 1 shows a very red continuum, steeper than in any Kennicutt galaxy, a strong break, as well as strong Naλ5892 and Hα emission lines. Note that the

image shows a regular morphology, and therefore the spectral classification provides additional physical information. Galaxy # 2 presents a very low S/N ratio which is just at the chosen limit for sample 1 (S/N $\gtrsim$ 5.0). The unusual continuum shape of this spectrum is probably responsible for the deviation from the sequence but the low S/N ration does not allow any further study. Galaxies # 3, 4, 6 and 7 exhibit Markarian signatures (galaxies with bursts of star formation). The continuum shape and absorption bands, typical of these galaxies, are clearly seen in Fig. 18 and are comparable to other known spectra (see for example Contini 1996). Such objects have in general a spiral morphology (Contini 1996), which is in marked contrast with the I(E) spectral type of objects # 3 and 4. This shows that, for galaxies which significantly deviate from the PCA spectral sequence, the spectral/morphological relationship is no longer valid. Object # 5 is a star which was willingly introduced in the sample as a test, and as we can see, it is far from the main
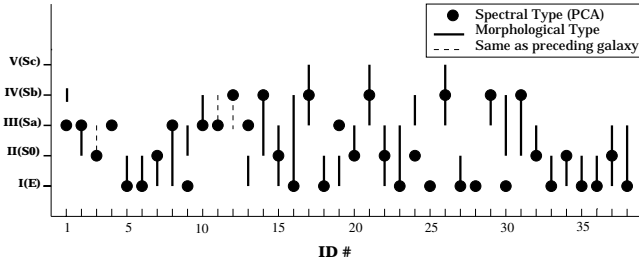
Fig. 17. Comparison between the morphological and spectral classification for the 35 galaxies listed in Table 7 and displayed in Fig. 16. There are 35 galaxies and 38 spectra, some galaxies having more than one spectroscopic measure: dashed lines for the morphological classification indicate that the galaxy is the same as the preceding one, and the 2 (or 3) spectra provide 2 measures of the spectral type.

sequence. It provides an additional test of the capability of the PCA to distinguish abnormal spectra. Galaxy # 8 is a typical galaxy with strong star formation. Note that Hα was blanketed by a sky line. Galaxy # 9 resembles a QSO at $z \sim 0.51$, if one identifies the broad emission line with MgII.

Other objects generally labeled as peculiar are the AGN (Seyfert, LINER's, N galaxies, etc...) and the E+A galaxies (see Zabludoff et al. 1996). As discussed in Sect. 6.3, the AGN galaxies are included in the "emission-line sample". The PCA is an excellent tool to detect these objects and quantify their spectral features via the 3rd PC. The E+A galaxies are however difficult to identify from the PCA classification. Because *classical* E+A galaxies have strong Balmer absorption lines, but *no* emission lines in the region 3500 to 7000 Å, these galaxies lie inside the normal sequence of early to intermediate-type galaxies (see Fig. 3). In order to identify the E+A galaxies in the ESS sample, we have measured the equivalent width of Hβ, Hδ and Hγ for the galaxies of sample 1, using a similar criterium to that used by Zabludoff et al. (1996): W[Hδ] ≥ 5 Å and no sign of [OII] emission. We found 9 galaxies which satisfy the selection criterium. The PCA spectral type of these galaxies is, except in one case, V/Sb. These galaxies imply a 3% fraction of E+A galaxies in the ESS in the redshift range $0.1 < z < 0.5$. This is in marked contrast with the 21 E+A out of 11113 field galaxies found by Zabludoff et al. in the Las Campanas Redshift Survey to $z \sim 0.2$, which gives $\sim 0.2\%$ of E+A galaxies. Two E+A candidates of sample 1 have $z \leq 0.20$, and the fraction does not change if we consider the 66 galaxies of sample 1 with $z \leq 0.20$. Because of the large redshift of these objects ($0.2 \lesssim z \lesssim 0.42$), the CCD images of these galaxies subtend too small solid angle for a detailed morphological study. Although we do not see evidence of merging, four galaxies form two different pairs, and so we cannot discard the possibility of interaction between some of the E+A galaxies and their neighbors. The other E+A do not show evidence of interaction.

We have verified that all of the objects which strongly deviate from the sequence in which lie the normal galaxies are indeed peculiar objects. On the other hand, the spectra of the objects which lie inside the spectral sequence were visually inspected

and do not show signs of any peculiarity, except the possibility that they could have strong absorption lines (for example E+A galaxies). The PCA is therefore efficient at detecting in a quantitative manner both the normal and most frequent objects, and the rare and peculiar objects.
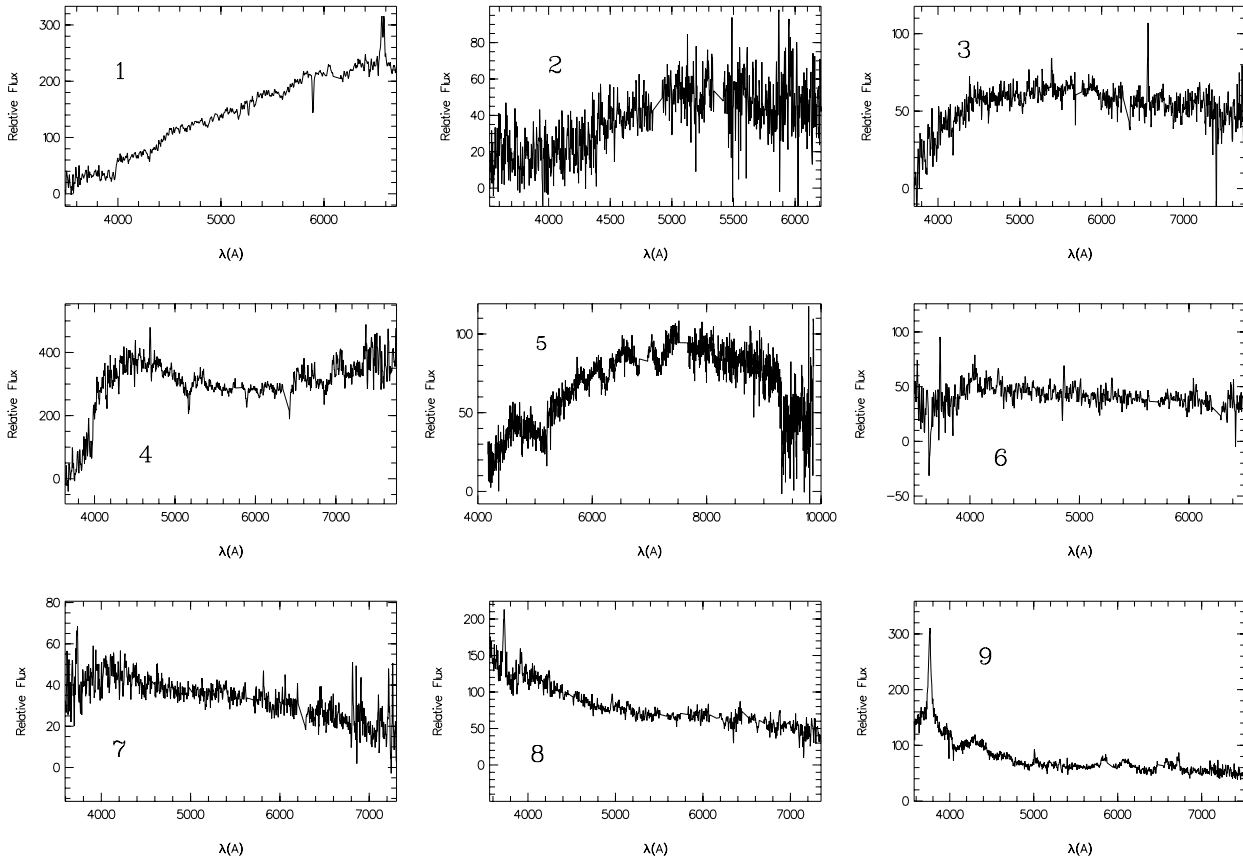
7. Discussion

7.1. Aperture bias

When performing a spectral classification, one must keep in mind that, in general, galaxy slit spectroscopy provides only a partial sampling of the objects. Here we comment on some of the biases which could be present in the spectra, and could produce an erroneous interpretation of the results. Two different phenomena produce what is called an "aperture bias". A first bias originates from the fact that the gathered light from galaxies at different distances, sampled with a slit of fixed width (in our case 1.3″ to 1.8″), correspond to different spatial extensions (and stellar populations) in the corresponding galaxies (this is called "aperture bias" hereafter). A second bias (called "orientation bias" hereafter) comes from the varying spatial orientation of the slit with respect to the observed galaxies due to observational constraints (see Fig. 16). In order to study the aperture bias, Zaritsky et al. (1995) have made some simulations for characterizing the influence of the size of an optical fibre onto their spectral classification for galaxies with $0.05 \lesssim z \lesssim 0.2$. Following their conclusions, our slits of 1.3″ to 1.8″ should not cause any significant aperture bias for galaxies with $z \gtrsim 0.1$. Moreover, the slits used for the ESS observations contain $\gtrsim 95\%$ of the bulge and disc emission for a typical face-on spiral of ~ 20 kpc in diameter at $z \gtrsim 0.1$ (for spirals with other orientations, the fraction of the bulge and disk sampled is even larger). Therefore the results presented here are weakly affected by the aperture bias. For elliptical galaxies, the "orientation bias" is null, because the stellar constituents generally have uniform distributions along the galaxy extent. On the other hand, for spiral galaxies, the early and late stellar populations are not equally distributed along the galaxy profile, and slits oriented along the minor axis will over-sample the bulge of the galaxy with respect to the disc. In this case, and assuming a standard morphological-spectral relationship, the young stellar populations are under-sampled and therefore the spectral type would appear earlier than the morphological type, or at least, earlier than the real integrated spectrum. This effect could have important consequences in the fraction of types found as elliptical and spiral. Observing our CCD images, along with the slit orientations, allows us to conclude that an orientation bias could exist for spiral galaxies which have $z \lesssim 0.1$ (where only a fraction of the galaxy profile is inside the slit). However, less than 4% of the ESS galaxies have $z \lesssim 0.1$. We emphasize that only a rigorous study of the data from spectro-imaging surveys can quantify both the aperture and orientation bias present in existing and future redshift surveys (see Hickson et al. 1994).

Table 8. Peculiar objects revealed by the PCA.

#	z	R_c	B_j-V_j	V_j-R_c	B_j-R_c	Spec. Type(PCA)	$PCA_{error}^{(c)}$	Morphology
$1^{(a)}$	0.12	18.36	1.17	0.74	1.91	I(E)	0.003	S0/Sa
2	0.41	20.35	1.24	1.37	2.61	I(E)	0.023	E/Sa merger
3	0.20	19.78		0.69		I(E)	0.010	E/Sa merger
$4^{(b)}$	0.19	17.56		1.10		I(E)	0.016	S0/Sa
5	–	19.87	1.28	0.77	2.05	II(S0)	0.014	star
6	0.21					V(Sc)	0.011	
7	0.21	20.47	0.64	0.42	1.06	V(Sc)	0.010	Sa/Sb + jet?
8	0.24	19.46	0.02	0.82	0.84	VI(Sm/Im)	0.011	Sa/Sb Pec + merger
9	0.51?	19.43	0.27	0.05	0.32	VI(Sm/Im)	0.048	Stellar profile+merger

Notes:

$^{(a)}$ Same as galaxy # 30 of Table 7.
$^{(b)}$ Same as galaxy # 9 of Table 7.
$^{(c)}$ Interval error in the PCA reconstruction, as defined in Eq. (7) (see Sect. 6.1).

Fig. 18. Galaxies deviating from the general trends of the ESS spectral characteristics, in rest-wavelength.

7.2. Comparison with other surveys

The fraction of different galaxy types found in the ESS sample may be compared to those found in other redshift surveys. Table 9 shows the fractions of the different morphological types found in the 6 other redshift surveys which provide the adequate information for comparison with the ESS data. For the ESS sample, we assimilate the spectral type with the corresponding morphological type from the Kennicutt average templates used for the classification. When examining Table 9, the reader should be aware of the different classification criteria used in the various surveys. Moreover, some morphological differences are subtle and can only be distinguished from high-quality imaging. The uncertainties in a given morphological type are in general not provided. However, some studies (Naim et al. 1995, and references therein) have shown that, when comparing the morphological classification of nearby galaxies by 6 different experienced astronomers, the r.m.s. scatter between two observers is

typically 2-T units (de Vaucouleurs 1959). In the case of deep surveys, the errors in the classification are complicated by the appearance of new morphological types as in the case of HST images (see van den Bergh 1997), and/or by the image quality (Dalcanton & Shectman 1996). For the ESS, we are able to check and quantify the different error sources. The major error originates from the flux calibration, whose *measured* uncertainty leads to an absolute error in the type fractions of $\sim 5\%$ (see Sect. 6.1).

We first examine the non-uniform binning. Given our classification errors for elliptical and spirals ($\sim 5\%$ of the fraction in each class), the fraction of E/S0 is comparable to that given by RSAC and by the faint DWG (references in the Table 9). Clearly, we found more ellipticals than Griffiths et al. and than in the HDF, as expected from the fainter limiting magnitude of the 2 surveys. In these cases the large number of spirals is due to the combination of evolution and "morphological K-corrections": in the case of the HDF, the survey is sampling the UV spectral bands, which trace the peculiar morphologies related to the star-forming regions within the galaxies, (see van den Bergh 1997). On the other hand, the fraction of E/S0 in the ESS is smaller than the fraction found in the CfA1 and CfA2 surveys. For the CfA2 survey, the fraction of ellipticals is larger probably due to the fact that the eyeball classification is performed from photographic plates, and some proportion of spirals is likely classified as ellipticals due to the disappearance of the spiral arms when the bulges are saturated (Huchra et al. 1995). The fraction of spirals (Sa/Sb/Sc) in the ESS sample is quite similar to that for the RSAC but is significantly larger that in all other surveys. The number of Sa/Sb/Sc for the ESS sample probably includes some fraction of Sd galaxies, because this morphological type is absent from our classification (see Table 4 and Sect. 6.1).

It is interesting to note that if we consider the classification provided by the uniform binning in the δ parameter (see §6.1 and last row of Table 9), our fractions of E/S0 and Sa/Sb/Sc agree quite well with the respective fractions for the CfA1 survey. However, we emphasize that such a uniform binning system is not realistic, in the sense that we obtain a poor correlation between the spectral properties and the morphological type. This leads to the important issue of the discreteness of type definition. It has been shown (Morgan & Mayall 1957, Aaronson 1978, Abraham et al. 1994), and we confirm in this paper, that the spectral *and* morphological properties span non uniformly but continuously over most sets of parameters used for classifying galaxies. The assignment of a type in the Hubble system suffers from an artificial discretization which can lead to significant differences depending on the classification procedure which is adopted. This is the case for the E/S0/Sa types, for which the spectral properties show small variations due to the small changes in the stellar populations among these types (this is confirmed by the small range in δ describing these types; see Fig. 8).

The ESS tends to have a similar type distribution to that observed in local or intermediate redshift surveys, as the CfA1, the RSAC, and the DWG survey. This seems to indicate that the galaxy distribution as a function of type is rather stable up to $z \sim 0.5$. Other surveys indeed indicate that up to this redshift, only a marginal galaxy evolution is present (Hammer et al. 1995, Hammer et al. 1997, Lilly et al. 1996): the [OII] equivalent width does not increase significantly and galaxy types are roughly uniform. The comparison of the ESS spectral classification with other surveys constitutes not only a test of our classification procedure, but also provides a quantitative insight into the origin of the observed differences, which can be related to galaxy evolution and the well-known morphology-density relation (Postman & Geller 1984). These effects will be further investigated in forthcoming papers.

8. Conclusions and prospects

In this paper we show that we can classify the galaxies of the ESO-Sculptor survey (ESS) from their flux calibrated spectra using the Principal Component Analysis (PCA) technique. The PCA allows to define a *continuous* spectral sequence highly correlated with the Hubble morphological type. This sequence can be written as a linear combination of a reduced set of parameters and vectors (3) which account for $\sim 98\%$ of the total flux of each spectrum. The parameters are also sensitive to the strength of emission lines. Our main results can be summarized as follows:

(1) Using Kennicutt spectra for galaxies of known Hubble types, we establish the strong correlation between the spectral galaxy type and the underlying old (red) and young (blue) stellar population within the galaxy. These populations can be quantitatively separated in the PCA approach using a sequence which arises mainly from the changes in the shape of the continuum and the relative strength of the absorption features.

(2) By application to the ESS data, we show that the PCA is a flexible and powerful tool to classify galaxies using the spectral information. Galaxies can be classified using one continuous parameter (δ). We also find that the presence and strength of the emission lines are correlated with the spectral type (late galaxies tend to have strong emission lines), and can be quantified by a second continuous parameter (θ). The continuous nature of the classifying parameters δ and θ provides a powerful tool for an objective study of the systematic and non-systematic properties (*i.e.*, peculiar objects) of spectral data. Moreover, it allows us to use one (or two) fundamental parameter(s) to construct an analytical relation between the classification parameter(s) and other quantitative properties of the galaxies (for example K-corrections, local galaxy density, etc...).

(3) We illustrate using the ESS data how the PCA acts as a powerful filter of noisy spectra, inherent to deep redshift surveys. Reconstruction of the ESS spectra with 3 principal components increases the S/N from the range 8-20 to the range 35-80.

(4) The spectral sequence given by the PCA is not uniformly populated: the early types are more concentrated in the classification plane than the late types. This non-uniform distribution of the different *spectral* types is closely related to

Table 9. Different morphological mix obtained by other surveys. The ESS classifications are summarized in the last 2 rows. All the type fractions are percentages.

Source	Magnitude[a]	E/S0	Sabc	Sd/Irr	Sp/Irr[b]	Unclassified
CfA1[c]	$m_z \leq 14.5$	35	54	10	65	1
CfA2[c]	$m_z \leq 15.5$	42	48	8	56	2
RSAC[d]	local	29			71[b]	
Shanks[e]	$m_{bj} \leq 16.0$	43	45	12	57	0
Griffiths[f]	$m_I \leq 22.25$	19	44	13	57	25
DWG faint[g]	$m_I \leq 21.75$	28	50	14	66	6
HDF[h]	$m_I \leq 24.5$	16	37	47	84	0
ESS[i]	$m_R \leq 20.5$	26	71	3[k]	74	0
ESS[j]		38	55	7[k]	62	0

[a] Limiting magnitude for the classification.

[b] Sa/Sb/Sc/Sd/Irr.

[c] Marzke et al. 1994.

[d] Sandage & Tammann 1981.

[e] Shanks et al. 1984.

[f] Griffiths et al. 1994.

[g] Driver et al. 1995a.

[h] Hubble Deep Field. Driver et al. 1995b.

[i] ESO-Sculptor Survey, using the non-uniform rebinning of column 6 of Table 4.

[j] ESO-Sculptor Survey, using the uniform rebinning of column 2 of Table 4.

[k] Sm/Irr types.

the fact that systematic differences between two consecutive *morphological* types are larger among spiral galaxies than among elliptical or lenticular galaxies. This leads to construct a variable binning when comparing the observed spectral sequence with morphological classifications from other surveys.

(5) When making the analogy between spectral type and morphology via the Kennicutt spectra, we find that the ESS sample contains $26\pm7\%$ of E/S0, $71\pm9\%$ of Sa/Sb/Sc and $3\pm7\%$ of extreme late spirals (Sm/Im). The type fractions for the ESS show no significant changes in the redshift interval $z \sim 0.1 - 0.5$, and are comparable to those found in other galaxy surveys at intermediate redshift. For the ~ 277 galaxies in the ESS analyzed here, the dominant type is Sb, followed by Sc, Sa, and early types. We do not detect any strong evolution in the ESS data as a function of redshift, up to the depth of the ESS spectroscopic catalogue ($z \sim 0.5$). Other surveys have detected only a marginal evolution at $z \lesssim 0.5$, like the CFRS (Lilly et al. 1996) and the Autofib survey (Heyl et al. 1997), and significant evolution appears to occur at $z \gtrsim 0.4 - 0.6$. In the ESS sample, we note a significant excess of early types at $z \sim 0.4 - 0.5$. The nature of this excess will be further investigated in a future paper using the complete redshift sample.

Application of the PCA method to the ESS shows that it may be applied to any set of flux-calibrated spectra, and that it is a promising technique for on-going and future massive galaxy surveys. The major interest of the PCA technique is that the spectral trends followed by the sample used are independent from any set of templates (the classification space is continuously populated). The PCA technique therefore offers clear advantages over other discrete methods like the χ^2

(see Zaritsky et al. 1995) or the cross-correlation method (see Heyl et al. 1997), which are fully dependent on the set of templates used: in these approaches, it is difficult to discriminate differences in the results from differences in the input templates. Also, such classification procedures are sensitive to fluctuations due to the noise of each target spectrum, an undesirable phenomenon. In contrast, the PCA offers an unsupervised classification system (Naim et al. 1995), in which one does not make any assumption on the general trends followed by the sample. Moreover, the PCA classification shows that the spectral sequence is essentially determined by the variations in the shape of the continuum. Any spectral classification method dependent only on the strength of the absorption lines (Zaritsky et al. 1995, Heyl et al. 1997) is therefore very sensitive to instrumental effects and/or physical phenomena not necessarily correlated with spectral type, and must be interpreted with caution.

The spectral classification for the ESS sample will be used to derive precise K-corrections, which are fundamental for deriving absolute magnitudes. Those in turn will allow to calculate the luminosity functions as a function of spectral type (in a subsequent paper). With the specific galaxy luminosity function, we can investigate in detail the morphology-density relation in the field (see Marzke et al. 1994) and more generally the variations in galaxy properties with local environment and location within the large-scale structure. These various analyses will be reported in subsequent papers.

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