STRÖMGREN PHOTOMETRY FROM $z = 0$ TO $z \approx 1$. I. THE METHOD

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ABSTRACT

We use rest-frame Strömgren photometry to observe clusters of galaxies in a self-consistent manner from $z = 0$ to $z = 0.8$. Strömgren photometry of galaxies is intended as a compromise between standard broadband photometry and spectroscopy, in the sense that it is more sensitive to subtle variations in spectral energy distributions than the former, yet much less time-consuming than the latter. Principal component analysis is used to facilitate extraction of information from the Strömgren data. By calibrating the principal components using well-studied galaxies, as well as models of stellar populations, we develop a purely empirical method to detect, and subsequently classify, cluster galaxies at all redshifts smaller than 0.8. Interlopers are discarded with unprecedented efficiency (up to 100%). The first principal component essentially reproduces the Hubble sequence and can thus be used to determine the global star formation history of cluster members. The (PC2, PC3) plane allows us to identify Seyfert galaxies (and distinguish them from starbursts) based on photometric colors alone. In the case of E/S0 galaxies with known redshift, we are able to resolve the age-dust-metallicity degeneracy, albeit at the accuracy limit of our present observations. We use this technique in later papers to probe galaxy clusters well beyond their cores and to fainter magnitudes than spectroscopy can achieve, because the faint end of the luminosity function as well as the outer cluster regions seem to exhibit the strongest evolutionary trends. We are able to directly compare these data over the entire redshift range without a priori assumptions because our observations do not require first-order k-corrections. The compilation of such data for different cluster types over a wide redshift range is likely to set important constraints on the evolution of galaxies and on the clustering process.

Subject headings: galaxies: clusters: general — galaxies: evolution — galaxies: fundamental parameters — galaxies: photometry — methods: data analysis — techniques: photometric

On-line material: machine-readable tables

1. INTRODUCTION

The study of galaxy evolution has benefited greatly from observations of galaxy clusters, because of better statistics (compared to pencil beam surveys), and because clusters are more easily identified than isolated galaxies at large redshifts (e.g., Couch et al. 1983; Dressler 1993). These studies revealed some of the most spectacular galaxy evolutionary trends, such as the Butcher-Oemler effect (Butcher & Oemler 1978). Since then, clusters of galaxies have been used as benchmarks to sample galaxy evolution at different redshifts (e.g., Butcher, Oemler & Wells 1983; Dressler et al. 1999).

However, data on galaxies in clusters are usually limited to the inner regions and/or to the brighter cluster members because of technical constraints; these selection effects bias the selection and comparison of clusters at different redshifts, as the fields of view and apparent magnitudes translate into different metric sizes and luminosities. The observed changes may therefore not be straightforward to interpret in terms of galactic evolution (e.g., Andreon & Ettori 1999). Moreover, the galaxies are probably affected by the evolution of clustering itself. The modern view of hierarchical clustering (e.g., Baugh, Cole, & Frenk 1996) suggests that the latter might outweigh the former. Thus, many degeneracies, both intrinsic and technical, plague the study of distant cluster galaxies. By intrinsic, we mean the difficulty to decide whether the observed redshift evolution of the galaxies is due to cosmological galaxy evolution, or rather the result of environmental effects, i.e., changes in cluster properties that affect the galaxies in it. Resolving this issue requires a coverage of the parameter space (redshift, cluster type, radial dependence, . . .) that does not yet exist.

The method described below is aimed at bringing this kind and quantity of data within reach. It is an observing and analysis technique that enables one to probe the luminosity function of fainter objects than can be reached spectroscopically, as well as to cover more sparsely populated regions, such as poor clusters and the outskirts of rich ones, in a consistent manner for all redshifts up to $z = 0.8$ (instrumental limitation). It conserves the advantages of classical photometry (depth and spatial coverage) but avoids its usual pitfalls, such as field contamination, k-corrections, and loss of essential spectral information.

This paper is organized as follows; §2 outlines the advantages of our rest-frame photometric observing technique. In the following sections we describe the properties of such data using principal component analysis (PCA): in §3 we show how to define cluster members in principal component space (the “cluster-box”) and demonstrate how effi-
ciently stars as well as fore- and background galaxies are recognized in this new parameter space. After eliminating the interlopers, we show, in § 4, how to differentiate the various types of cluster members in that same parameter space, which is necessary to address questions of galaxy evolution. Effects of age, dust, and metallicity, as well as AGN activity are discussed. Section 5 summarizes the method.

2. A NEW APPROACH TO EXtragalactic PHOTOmetry

2.1. Limitations of Standard Broadband Photometry

A spatially resolved galaxy spectrum is the richest information harvest an observer can hope for. However, at \( z \gtrsim 0.3 \) galaxies are barely a few arcseconds in size, and one has to settle, in most cases, for a single aperture spectrum. Ideally, one wishes to obtain the spectra of all the galaxies in a given cluster, thereby determining their redshift and cluster membership, and infer their star formation histories by comparing these spectra to evolutionary models. Unfortunately, even with the largest telescopes, this requires unreasonably large amounts of observing time, if one wishes to cover the entire range of cluster types and redshifts. Moreover, multislit or fiber spectroscopy introduces a selection bias by rendering simultaneous observations of close pairs or subgroups technically difficult and time consuming, because of adjacency limitations due to the physical size of the fibers. Aperture effects, related to the fraction of the galaxy being sampled at different distances, slit position, etc., constitute additional complications.

The usual alternative is broadband photometry, with which the pioneering work on distant galaxy clusters has begun. However, the gain in time offered by this method is often outweighed by the loss of spectral information. First, most existing studies deal with field contamination only statistically (e.g., Wilson et al. 1997). Although photometric redshifts are in principle of good quality (see e.g., Connolly et al. 1995), they rely heavily on the \( U \)-band to catch the 4000 Å break at \( z \lesssim 0.4 \) or the rise in UV flux of star forming galaxies for \( z \lesssim 0.6 \), but the \( U \)-band is usually not used in high-z cluster observations aimed at the visible range of the cluster galaxy’s SED.

Second, the large width of standard broadband filters causes smearing of spectral information. Hence, comparing photometric data to evolutionary synthesis models suffers from various degeneracies, such as the age-metallicity degeneracy (Worthey 1994).

An additional major problem arises when comparing photometric data from clusters at different redshifts, because the standard filters sample completely different regions of the rest-frame spectra. Such comparisons require large k-corrections, which are extremely morphology dependent and presumably also evolution dependent. In fact, they require a priori knowledge of the evolutionary effects one is looking for, a circular argument. In some lucky cases, standard filters at one redshift correspond roughly to other standard filters at another redshift (e.g., Stanford, Eisenhardt & Dickinson 1995, 1998), yet differential k-corrections still have to be made, and the data sets thus generated are somewhat heterogeneous and of limited common spectral coverage.

Lastly, the comparison of galaxies at various redshifts in search for evolutionary effects requires a meaningful selection criterion, which is valid over the entire \( z \)-range. This, too, is plagued by the inherent uncertainty of the k-corrections, which differ by up to 1 mag for different Hubble types (de Vaucouleurs, de Vaucouleurs, & Corwin 1976).

2.2. The Strömgren Photometry

Rakos and coworkers have pioneered an observing technique that resolves, or at least alleviates, some of the aforementioned problems: extragalactic rest-frame Strömgren photometry (see Rakos & Schombert 1995 and references therein). Unlike the Johnson system, the Strömgren filters have been intentionally designed to match specific signatures in the spectra of stars, that relate directly to the physical properties one wishes to investigate, such as temperature, metallicity, and surface gravity (Strömgren 1966). For technical reasons, Rakos et al. slightly modified the bandpass definitions, so that all four filters are now \( \sim 200 \) Å wide, and their central wavelengths are \( uz = 3500 \) Å, \( vz = 4100 \) Å, \( bz = 4675 \) Å, and \( yz = 5500 \) Å, respectively. (The lower case \( z \) in the filter name refers to the rest frame of the source.) These slight modifications do not influence the interpretation of the photometry, therefore we will not systematically distinguish “Strömgren filters” from “modified Strömgren filters” hereafter. We will omit the \( z \) and refer to these bands as \((u, v, b, y)\), understanding implicitly that they are “tuned” to the rest frame of the target cluster.

Rakos, Schombert, & Kreidl (1991), Rakos & Schombert (1995), and Rakos, Maindl & Schombert (1996), describe the original stellar interpretation of Strömgren fluxes and colors, and show how the same quantities can be used to characterize extragalactic objects. Briefly, for homogeneous stellar populations, the \((u - v)\) color measures the strength of the 4000 Å break, which can be used as an indicator of recent star formation. The \((b - y)\) color measures the slope of the continuum redward of the break. The \( b \) and \( y \) filters are situated in regions free of any prominent absorption features, thus \((b - y)\) should be a good indicator of mean stellar age, free of metallicity effects. The \( v \) filter, on the other hand, contains the region of the FeI + CN line blend. The photometric index \( m = (v - b) - (b - y) \) can therefore be used to measure metallicity effects. Needless to say, when measuring real galaxy SEDs the colors are less straightforward to interpret, as the effects of mixed stellar populations and internal dust extinction are difficult to account for. For example, the H\( \alpha \) line present in the spectra of hot stars introduces an age-dependence in the \( v \) filter. Therefore, we will rely in what follows on a more empirical approach.

In summary, the main advantages of this observing technique are (1) the filters are designed to sample spectral regions, which are very sensitive to changes in the underlying physical properties, (2) these filters avoid all strong emission lines, which cause confusion in standard UVB photometry of active galaxies, and (3) observations are carried out at fixed rest-frame wavelengths, thus avoiding the uncertain k-corrections and delivering a self-consistent data set over the entire redshift range covered. Of course, this requires a priori knowledge of the cluster’s redshift.

With optical telescopes + cameras, the rest-frame Strömgren method can be applied to clusters from \( z = 0 \) to \( z \sim 1 \). However, the redshift segments \( 0.36 < z < 0.41, 0.60 < z < 0.66 \) and \( 0.83 < z < 0.89 \) need special attention because of the atmospheric A-band contaminating the redshifted \( y, b, \) or \( v \) filter, respectively. This can in principle be calibrated out with an adequate spectrophotometric standard star, otherwise, these regions should be avoided.
3. IDENTIFICATION OF CLUSTER MEMBERS VIA PCA

The basic approach adopted here is to assume that cluster galaxies concentrate in a specific location of the three-dimensional space defined by the Strömgren colors. We demonstrate this below for a number of field and cluster galaxy samples.

3.1. From Colors to PCA Space: Definition of the “Cluster-Box”

We collected large aperture spectra from the literature (Kennicutt 1992a, 1992b and Kinney et al. 1996) and convolved them with synthetic Strömgren filter response curves, to simulate the appearance of known galaxy types in the three-dimensional \((u-v), (v-b), (b-y)\) color space (Fig. 1). The details of the samples are given in Tables 1 and 2. We insist on the “large aperture” selection criterion (although it limits the statistics of the template sample) because we will subsequently compare them to high-redshift aperture photometry, and we want to avoid aperture-related color effects. Indeed, the color difference due to varying aperture sizes can be larger than the intrinsic color difference of different galaxy types observed through a constant aperture (see, e.g., de Vaucouleurs et al. 1976 and Brosch & Shaviv 1982). This effect is expected to be even more severe in Strömgren colors, which are more sensitive to differences in stellar population (and their gradients). As will be shown at the end of this section, the sample nevertheless covers well the entire range of nearby galaxy types.

It is clear from Figure 1 that the ensemble of galaxies occupies a well confined, but difficult to fathom subspace, which we now want to define in the simplest possible way. Since the default coordinate system (consisting of the three axes \(u-v, v-b, \) and \(b-y\)) is impractical for this purpose, we performed a principal component analysis (PCA) on the data points.

Briefly, a PCA, in any \(n\)-dimensional space, calculates the axis along which the data points present the largest, most significant scatter. This is called the first principal component (PC1). It then proceeds to calculate PC2, the axis of the second most significant spread in the remaining \(n-1\) dimensional space orthogonal to the first PC, and so on. Mathematically, this is done by normalizing the coordinates of the data points to standardized variables and calculating their covariance. The final output are the eigenvectors (the PCs) and eigenvalues of this covariance matrix. If, at one point, the standard deviation of the \(m\)th PC is no larger than the accuracy of the data, it means that the data can be fully described by only \(n-m\) components. The gain of the PCA is therefore twofold: (1) it minimizes the dimensionality of the data and (2) it provides an orthonormal coordinate system in which the data are most easily

| TABLE 1 | THE KENNICUTT GALAXY SAMPLE |
|---|---|
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| TABLE 2 | KINNEY ET AL. GALAXY TEMPLATES |
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Fig. 1.—Three-dimensional view of the Kennicutt and Kinney galaxies in classical Strömgren color-space. The galaxies occupy a well-constrained subspace, inside which they are ordered roughly according to Hubble type, with early types in the upper right corner. The projections onto the three subplanes are also shown in gray. As explained, such color coordinates are impractical for a quantitative description. Symbols are as follows: circles, E and SO; upward-pointing triangles, Sa-Sb; downward-pointing triangles, Sc-Sd; diamonds, Im; squares, I0; pluses, unspecified Spiral; stars, the Kinney et al. starburst templates. The classification is taken from NED. Open symbols, galaxies with reported Seyfert(2) nucleus; filled symbols, no reported Seyfert activity.
characterized. The reader is referred to Lahav et al. (1996) for a more detailed description of PCA in an astronomical context.

The base vectors of the new coordinate system, in which we will from now on view the data, are

\[
\begin{align*}
PC1 &= 0.80(u - v) + 0.53(v - b) + 0.28(b - y) \\
    &= 0.8u - 0.27v - 0.25b - 0.28y , \\
PC2 &= -0.56(u - v) + 0.49(v - b) + 0.67(b - y) \\
    &= -0.56u + 1.05v + 0.18b - 0.67y , \\
PC3 &= 0.22(u - v) - 0.69(v - b) + 0.69(b - y) \\
    &= 0.22u - 0.91v + 1.38b - 0.69y .
\end{align*}
\]

Figure 2 gives a view of Kennicutt’s and Kinney’s galaxies in this new coordinate system (PC-space). Note that the only difference between Figures 1 and 2 (i.e., the transformation matrix between color-space and PCA-space) is a simple three-dimensional rotation. Yet, Figure 2 appears much simpler! The PC-space not only renders features more easily identifiable to the eye, it also facilitates automatic machine treatment of the data by providing a set of independent variables. The new coordinates being a linear combination of the original ones, we refer to them as “colors” too in what follows. Note that PC2 and PC3 can also be understood as curvature indices, as in Koo (1985).

Since galaxy spectra vary continuously along (and across) the Hubble sequence (Kennicutt 1992a, 1992b), the color space they occupy must also be continuous. We therefore choose to define the allowed space for cluster galaxies as the box defined by the maximal extent of the distribution in the new coordinate space (see Fig. 2). Because our observations are made at fixed rest-frame wavelengths, this cluster-box is essentially invariant with redshift. One might argue that differential k-corrections will still have to be made, because the rest-frame width of our filters changes with redshift, but these corrections (1) are very small, and (2) can easily be avoided by redshifting the template spectra and recalculating their colors. This will only be required if high-precision photometry \((dm \sim 0.01–0.02)\) is available or for comparisons of clusters over \(dz > 0.4\). If one wants to avoid this additional computation step, it is permissible to simply use the values obtained for templates shifted to \(z = 0.4\) (the middle of our redshift range). As can be seen in Figure 3, the differences in PC-colors due to the spectral stretching are negligible in most cases and can be accounted for by a slight widening of the cluster-box boundaries when the difference for certain spectral types becomes of the order of the PC-color accuracy.

In PC-space, the averages and standard deviations of the galaxies’ coordinates are

\[
\begin{align*}
\langle PC1 \rangle &= 0.35 , \quad \sigma_{PC1} = 0.45 , \\
\langle PC2 \rangle &= -0.18 , \quad \sigma_{PC2} = 0.10 , \\
\langle PC3 \rangle &= -0.08 , \quad \sigma_{PC3} = 0.05 .
\end{align*}
\]

Thus, the color-space occupied by “normal” galaxies (all but AGNs) is almost two-dimensional. The first two PCs alone contain 93.8% and 4.9% of the data’s variance, respectively, and together account for 98.7% of the total variance. This means that, in practice, a two-dimensional parameter space suffices to describe the entire range of Hubble types and the different subgroups therein. In fact, one single combination (PC1) is already extremely comprehensive! The ensemble of galaxies has the largest scatter (larger than in any original color-plane) in the (PC1, PC2) plane, which makes it useful for distinguishing among dif-

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**Fig. 2.—Galaxies in PCA-space.** The Kennicutt + Kinney sample viewed in three-dimensional PCA-space. The three projections onto the PC1-PC2, PC2-PC3, and PC1-PC3 planes are also shown in gray. Differences among galaxies now spread almost solely along one axis, PC1. High values of PC1 correspond to early-type galaxies, low values to late-type galaxies. The dispersion along PC2, and even more so along PC3, is much smaller. The standard deviation in PC3 is of the order of the measurement uncertainties in the data. This means, that \(\langle PC3 \rangle\) is an intrinsic galaxy “property,” which can be used to distinguish the ensemble of cluster galaxies from other objects, such as stars and field galaxies. The advantage of using PC-space instead of color-space is evident. The cluster-box, as defined in the text, and its projections are also shown. Symbols are as in Fig. 1.
different types of galaxies, as will be described in § 4. PC3 exhibits the smallest scatter, its standard deviation is of the order of the measurement uncertainties, and its full extent amounts only to 0.22 mag. Thus, PC3 can be used as a characteristic to separate cluster galaxies from other objects, as will be described in §§ 3.2 and 3.3.

The three PCA components define, therefore, a three-dimensional volume, which contains all the galaxy templates. We call this volume "the cluster-box," because the only condition we imposed on the SED templates was that they be at \( z = 0 \). Assuming that the spectral variety of local galaxies is representative of the evolution of galaxies from \( z = 1 \) to the present, the cluster-box ought to be invariant in rest-frame observations of distant cluster galaxies.

### 3.1.1. Robustness: Error Estimates

How are the PCs affected by measurement uncertainties in the input spectra? The noise in the four original bands being uncorrelated by definition, implies that

\[
M = S + N ,
\]

where \( M \) and \( S \) are the correlation matrices of the measured colors and the pure signal, respectively, and \( N \) (the correlation matrix of the noise) is diagonal, the \( i \)th term on the diagonal being the variance of the noise in the \( i \)th color. If the variance of the noise is the same for all colors, the eigenvectors of \( S \) and \( M \) are identical, i.e., the PC are unaffected by noise. However, it is more realistic to assume that the noise in \((u-v)\) is, say, twice as large, as in the two other bands. We have simulated this situation by creating 1000 mock sets of template spectra by adding random noise drawn from a normal distribution with FWHM = 0.1 mag for \((u-v)\) and FWHM = 0.05 mag for \((v-b)\) and \((b-y)\), the typical uncertainties in the colors derived from the Ken- nicutt spectra, and performed PCA on each one of these. The median deviation angles are 1\(^\circ\).3 for PC1, 4\(^\circ\).6 for PC2, and 5\(^\circ\).4 for PC3. The corresponding values and standard deviations for the coefficients of the PCs are

\[
\begin{align*}
PC1 &= 0.81(\pm 0.01)(u-v) + 0.52(\pm 0.01)(v-b) \\
    &\quad + 0.28(\pm 0.01)(b-y) \\
PC2 &= -0.56(\pm 0.02)(u-v) + 0.56(\pm 0.03)(v-b) \\
    &\quad + 0.61(\pm 0.04)(b-y) \\
PC3 &= 0.16(\pm 0.03)(u-v) - 0.65(v-b)(\pm 0.03) \\
    &\quad + 0.74(\pm 0.03)(b-y),
\end{align*}
\]

The small scatter proves that the cluster-box is very robust against uncertainties in the input spectra. For PC1 and PC2 this is not surprising, because it is an intrinsic property of PCA to cancel out uncorrelated variations (noise) in the presence of (correlated) variations in signal. Folkes, Lahav, & Maddox (1996) have shown that the high-order PCs, which are dominated by noise, can vary greatly in such simulations. In our case, however, the only noise-affected component is PC3, and since we are working in three-dimensional space, once PC1 and PC2 are established, the third component is fully determined. Thus, even PC3 is robust.

### 3.1.2. Completeness

Next, we want to verify whether the PC-space defined above is not too restrictive to include all possible galaxy types (our galaxy sample is quite conservative, because

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**Fig. 3a**

Second-order \( k \)-corrections of PC colors. Filters with central wavelengths tuned to fixed rest-frame spectral regions of galaxies at different redshifts, but of constant width, sample narrower bands of the galaxy’s spectrum with increasing \( z \). Panels (a), (b), and (c) show the differences in PC1, PC2, and PC3 due to this effect. Different symbols are used for each template spectrum. The dash-dotted lines indicate the uncertainties corresponding to \( d(u-v) = d(v-b) = d(b-y) = 0.05 \).
Kennicutt’s sample is restricted to local field galaxies, and spatially integrated spectra are otherwise rare in the literature. We therefore performed the same analysis on a list of Strömgren colors of 143 galaxies compiled by one of us (KR). This list includes 63 of the Kennicutt galaxies as representatives of normal galaxies, 41 Seyfert galaxies from de Bruyn & Sargent (1978), 17 dust-rich galaxies (IRAS sources) from Ashby, Houck, & Hacking (1992), as well as 37 nearby and distant cluster galaxies from Yee & Oke (1978) and Gunn & Oke (1975) to avoid any cluster/field or redshift bias (see Table 3 for details). Figure 4 summarizes the morphological breakup of the three tables in form of histograms. This sample covers a wider range of spectromorphological\footnote{The term “spectromorphological” denotes the fact that, although the original Hubble typing is based on morphology, its terminology is often applied to the spectral sequence of galaxies, because of the reasonable correlation between them.} types than the Kennicutt + Kinney et al. list, namely it contains strong AGNs, more starbursts, and cluster galaxies (cD’s, . . .). Such objects are known to be present in distant clusters, therefore we must ensure that the selection criterion described above, based on the cluster-box, is not biased against them. The disadvantage of the Rakos sample is that it does not always meet the large aperture condition. This is namely the case of the IRAS galaxies, the Seyfert spectra of de Bruyn & Sargent, and some of the Yee & Oke objects.

The space generated by all normal galaxies, as well as Seyfert 2’s, in this test sample is nearly identical to the original PCA cluster-box. In fact, all the galaxies of the Rakos sample, except pure Seyferts and some IR-bright galaxies, fall within the cluster-box defined above. In order to retain the aperture criterion, we will define the galaxy-PCA–space as the union of two subspaces, one of normal galaxies—as defined at the beginning of this section—and one of galaxies with active nuclei (Seyfert-box), as displayed in Figure 5. In the case of the latter, aperture effects are less important because most of the emitted light originates from a small nuclear region. Plotted also in Figure 5 are the IR-bright galaxies from Ashby et al. (1992). Some of them lie outside the cluster-box and are therefore visible (as crosses) in Figure 5. Visual inspection of their spectra reveals that they do not represent a distinct category of galaxies, but rather the highly dust-reddened versions of mixed AGN-starburst galaxies.

In summary, an object is identified as cluster member if it lies within either of the two boxes defined above. In a second step, one can “redden” the two boxes to search for dust-enshrouded cluster members. This makes our selection criterion essentially free of any evolutionary bias. There remains a possibility that a distant cluster might harbor a galaxy so peculiar that it resembles nothing we know from the local samples. We accept, as a caveat, that the membership selection might reject very few and very peculiar objects, but we consider such a possibility very unlikely and estimate that it will not influence significantly our evolutionary conclusions.

3.2. Star Contamination

Images of galaxy clusters will always be contaminated by foreground stars. Bright stars are easily identified and discarded, but faint ones can be mistaken for small, compact galaxies at high redshift, especially in observations with degraded spatial resolution.

The rest-frame observing technique can considerably alleviate this problem. The rest-frame ($z = 0.2$ to $z = 0.8$) Strömgren filters will sample the red portion of the stellar ($z = 0$) spectra, away from the distinctive features they were originally designed to match. This yields unrealistic stellar colors.

In order to investigate this further, we simulated stellar contamination by folding the theoretical flux distributions from the lcb97\footnote{http://www.astro.unibas.ch/~lejeune.} library of stellar atmospheres (Lejeune, Cuisinier & Buser 1997, 1998), covering spectral types O–M and luminosity classes I, III, and V, with the redshifted Strömgren filter response curves for $0.1 \leq z_{\text{obs}} \leq 0.8$. The lcb97 is the most complete stellar library to date, covering $2000 \leq T_{\text{eff}} \leq 50,000$ K, $-1.02 \leq \log L \leq 5.5$, and $-5.0 \leq \log Z/Z_{\odot} \leq +1.0$ in a uniform grid. In the three-dimensional PC-space no star lies inside the Seyfert-box and most stars lie well outside the cluster-box (empty space in Fig. 6). Figure 6 shows only those stellar types that are indistinguishable from galaxies in the redshift range $0.1 \leq z_{\text{obs}} \leq 0.8$. The conclusion is that in observations of clusters at any given redshift, only a certain subgroup of F, G, and K stars will contaminate the data. The precise spectral types of the intruding subgroup will depend on the redshift of the target cluster.

The actual number of such stars depends on galactic coordinates. This is dealt with statistically, as follows. For each cluster, the Bahcall-Soneira Galaxy model\footnote{http://www.sns.ias.edu/~jnb/Html/galaxy.html.} (Bahcall 1986) is used to predict the number of such stars along the

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**TABLE 3**

| The Rakos Galaxy Sample |
|-------------------------|
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Testing for completeness. The large box represents the cluster-box defined in Fig. 2. All normal galaxies from the Rakos test sample (see text) are located within this box and are therefore not visible in the plot. The smaller box below it encompasses the location in PC-space of Seyfert nucleus dominated galaxies. These two volumes do not overlap. The location of weaker Sys, which have a composite spectrum of AGN + host galaxy, can be explained by a simple combination of "pure" Seyfert and "pure normal galaxy" (see § 4 for a more detailed discussion). Also shown is the internal reddening vector for $A_V = 1$ (solid arrow) and its projections along each axis (dashed arrows), and the IR-bright galaxies (crosses). Such objects do not represent a separate class of galaxies but reddened versions of mixed AGN-starburst galaxies (again, see § 4).

line of sight. This model of the Milky Way is the combination of a disk and spheroid, each with its own luminosity function, that predicts the projected stellar number density versus apparent magnitude and $B - V$ color for given Galactic coordinates, as well as the breakdown between dwarf and giant stars. Despite its very simple assumptions, the model fits amazingly well the observed star counts (Bahcall & Soneira 1984).

Contamination by stars for observations with $0.1 \leq z_{\text{obs}} \leq 0.8$. The figure displays those stellar types that will be indistinguishable from cluster galaxies, based on their colors alone. The efficiency with which we can eliminate foreground stars is reflected by the emptiness of this figure.
This is best illustrated by an example: Cl0016+16, a cluster at $z = 0.54$, has been observed by KR at KPNO. At that redshift, only stellar types F8 I–K2 I, F2 III–K3 III, and F2 V–K4 V in the magnitude range $m(V) = 18.7–22.5$ (brightest cluster galaxy and limiting magnitude of the observation, respectively) can contaminate the galaxy counts. Figure 7 shows the projection of the sheet containing the stellar models onto the first two PCs. In this case, the field of view was $7 \times 7$ square arcminutes. The Bahcall-Soneira program predicts about 15 such stars within the frame. This is an upper limit, as the incompleteness at faint magnitudes has not been folded into the calculation. For our observations of A115 ($z = 0.191$, Rakos et al. 2000), covering a circular region of 10' in diameter, 2.6 stars brighter than $m(V) = 21.25$ (faintest object detected) are predicted to contaminate the cluster-box. This calculation takes the incompleteness function into account.

Since—as will be shown in § 4—different galaxy types occupy distinct regions of the cluster-box, we also know to which class of galaxies the stellar contamination correction needs to be applied, according to the position of these stars within the cluster-box.

Contamination by stars in the region of highly reddened cluster galaxies is not an issue, as stars have low PC2 values (see Fig. 7), whereas reddened objects have increasingly high PC2 values (see reddening vector in Fig. 10).

### 3.3. Redshift Discrimination

Probably the most severe weakness of cluster photometry is contamination by foreground and background galaxies, especially when trying to investigate the outskirts of clusters and/or its faintest members. Considerations of apparent size and magnitude do not help to resolve this issue, as both quantities change rather slowly with redshift beyond $z = 0.2$, while the intrinsic scatter at any given redshift is very large. The only constraint they yield is that galaxies brighter and/or larger than the first-ranked cluster galaxy can be immediately discarded as foreground, but the density of such field galaxies is so low that it hardly improves the situation. For the purpose of the following simulations, we have adopted $M_p$ (brightest) = $-22.68$ (Hoessel, Gunn, & Thuan 1980), $H_0 = 60$, and $q_0 = 0.5$. When dealing with real cluster data, we will replace this by the observed value.

Connolly et al. (1995) have demonstrated the efficiency of photometric redshift determinations, which rely mainly on the shifting of the 4000 Å break through the successive filter passbands. Along the same line of thought, Fiala, Rakos, & Stockton (1986) have used the marked difference in their $b-y$ and $mz$ indices to identify cluster ellipticals at various redshifts. However, the situation becomes less clear when dealing with the whole gamut of galaxy types, as intrinsic spectral differences become entangled with differences due to redshift. For early-type galaxies, the shifting (with redshift) of the 4000 Å break through the filter bandpasses makes cluster membership identification relatively easy, but this criterion becomes useless for active galaxies with flat spectra, as well as for any foreground galaxy, that is sampled only redward of the break. In the latter cases, one has to rely on a combination of more subtle features, such as emission and absorption lines, increasing the dimensionality of the problem. Here again, PC-space offers the most efficient cure.

In order to assess the efficiency of rest-frame Strömgren photometry at identifying, and subsequently discarding, interlopers from the list of cluster galaxies, we have artificially redshifted the Kinney galaxy template spectra from $z_{\text{gal}} = 0.0$ to $z_{\text{gal}} = 0.80$ in steps of $\delta z = 0.005$, to simulate field galaxies. We then simulated rest-frame cluster observations over that same redshift range ($z_{\text{obs}}$) and calculated for each template the PC-colors at every point in the ($z_{\text{gal}}$, $z_{\text{obs}}$) space. If the PC-colors of the redshifted template are inconsistent with the cluster-box, the field galaxy will be successfully identified as an interloper. The results are (pessimistically) summarized in Figure 8, which shows four representative examples. For each galaxy type we shaded that area in the ($z_{\text{gal}}$, $z_{\text{obs}}$) plane where the galaxy’s PCs lie inside the cluster-box. The patch along the principal diagonal ($z_{\text{gal}} = z_{\text{obs}}$) represents the correct identification of cluster members, the other patches are failures of the system to recognize field galaxies. Success is demonstrated by the emptiness of the figure. Photometric uncertainties (typically 0.05 mag) have been included in this calculation and make the interloper strips twice as wide as they would be in the ideal (zero error) case. The main conclusion is that our system recognizes background galaxies extremely well: only a small fraction of background starburst galaxies are not recognized. Foreground galaxies are more problematic, many will be mistaken as cluster members. This is not dramatic for low- and intermediate-redshift observations, because the foreground volume subtended by the image size is rather small, but it can be a problem for high-$z$ observations. Luckily, this will be somewhat balanced by the smaller magnitude range (to the detection limit) spanned by cluster members at high $z$. It is worth noting that 70% of the successful identifications are due to PC3 alone. Indeed, as stated in the previous section, the allowed range in PC3 for normal galaxies is very small and there is no visible trend of rest-frame-PC3 versus galaxy type. This means that PC3 is a characteristic quantity for any kind of galaxy (except AGNs) at the right redshift.

Since our field galaxy identifier is not perfect, we estimate in what follows the actual number of interlopers remaining

![Fig. 7.—Stellar contamination in Cl0016+16. Projection onto the (PC1, PC2) plane of the cluster-box and the stellar sequence. Different symbols are used to distinguish spectral types, and luminosity class is represented by the symbol size (large symbols for supergiants, intermediate size for giants, and small symbols for main sequence stars). Symbols are as follows: circles, O stars; pluses, B; crosses, A; upward-pointing triangles, F; squares, G; downward-pointing triangles, K; diamonds, M.](image-url)
after the rejection procedure. Approximately 15% of local field galaxies are currently undergoing starbursts (T. Contini 1998, private communication). The remaining 85% can be split according to their morphology into 8/10 spirals, 1/10 S0s, and 1/10 ellipticals (Sandage & Tamman 1979). This yields a spectrophotometric breakup of 15% starburst galaxies, 68% spirals and 17% ellipticals and S0s at $z = 0$. We estimate the redshift evolution of the spectro-morphological breakup based on the luminosity density evolution estimated by Lilly et al. (1996). They find that the contribution from galaxy types Sbc or later roughly doubles by $z = 0.75$–1.00 in the 4400 Å as well as in the 1 μm bands. Assuming a one-to-one relationship between luminosity density and number counts, we estimate that the fractional contribution of our starburst category also doubles, increasing to about 30% at $z = 1$ at the expense of the other types. Thus, we can calculate the fraction of field galaxies that our algorithm will recognize as a function of $z_{\text{gal}}$ and $z_{\text{obs}}$. Note that the zero-redshift estimate of the spectro-morphological breakup takes into account the typical completeness limits of our observations ($I_{AB} = 20–21$ mag), whereas its redshift-evolution is derived from the CFRS, which is complete to $I_{AB} = 22.5$. This causes us to somewhat overestimate the number of high-redshift, star-forming galaxies visible in our frames, due to the luminosity-dependence of galaxy evolution. However, as long as $z_{\text{obs}} < 0.7$, the field galaxy rejection mechanism works at nearly 100% efficiency for high-redshift ($z_{\text{gal}} > 0.7$) galaxies (Figs. 8 and 9), eliminating this uncertainty from the end result. "number of unidentifiable field galaxies." For $z_{\text{obs}} > 0.7$, the numbers quoted are upper limits.

Figure 9 shows the percentage of galaxies whose colors are within the cluster-box boundaries. The peak along the principal diagonal is produced by the cluster galaxies themselves. Success at identifying interlopers corresponds to low values in this figure. In order to explain the width of the peak, Figures 10a–10c show—for $z_{\text{obs}} = 0.1, 0.4$, and 0.7, respectively—the effect of small redshift deviations ($-0.1 \leq \delta z \leq 0.1$) about the cluster mean. The details depend on galaxy type and redshift of observation. Overall, background objects are more easily discarded than foreground, and early-type galaxies more easily than late-type galaxies. The regions of redshift space, where immediate foreground or background galaxies still fall within the cluster-box boundaries or into the Seyfert-box (see stb3 in Fig. 10a) are accounted for statistically.

We choose to normalize the fraction displayed in Figure 9 by the statistically complete spectroscopic subset of the Canada-France Redshift Survey (Lilly et al. 1995; Crampton et al. 1995) to obtain actual numbers. Its completeness

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**Fig. 8.**—Redshift discriminating ability. For selected galaxy templates, we show, for each redshift of observation ($z_{\text{obs}}$), the redshifts $z_{\text{gal}}$ at which this type of field galaxy will be indistinguishable from cluster members. The central strips, along the principal diagonal, correspond to galaxies for which $z_{\text{gal}} = z_{\text{obs}}$, i.e., cluster members. All quiescent background galaxies (upper panels) are successfully discarded, as are most starbursts.
limits ($17.5 \leq I_{48} \leq 22.5$) are consistent with our deepest cluster observations. Each cluster observation is limited by the flux of objects in its respective $yz$ filter, which corresponds to rest-frame $m_{5500}$. Therefore, each $yz$ filter “sees” a different portion of the field galaxies’ SED (depending on $z_{gal}$), which implies that the number of field galaxies seen in cluster observations varies with $z_{obs}$. The same procedure can be applied to the Seyfert-box separately. Figure 11 displays the number density of remaining interlopers in the cluster-box (pluses) and the Seyfert-box (crosses) in three magnitude bins, as a function of $z_{obs}$. The efficiency of our algorithm in rejecting interlopers varies between 50 and 100%, depending on the magnitude bin and redshift of observation. Note that this statistical estimate does not take into account the unknown, large-scale clustering features of the observed fields.

Contamination of the reddened boxes can be calculated the same way. Reddened Seyfert-boxes are essentially free of contamination, as well as cluster-boxes for $A_V > 1.5$. Less reddened cluster-boxes suffer very small contamination.

Our goal is to detect evolution in cluster galaxies. Hence, the question of interest is: What is the weakest evolutionary trend we can positively detect, in spite of the remaining interlopers? The answer depends not only on $z_{obs}$, but also on the overdensity in a given cluster region. In the central regions of rich clusters, field contamination is not an issue because the overdensity can reach a few hundred, but previous studies (Rakos, Odell, & Schombert 1997) indicate that the outer regions are of interest, because the preferred location of the star-forming galaxies constitutes an important clue to the physical processes at work. Figure 12 shows the fraction of unidentifiable interlopers likely to remain in our data sets after the cluster-box test, as a function of $z_{obs}$ and overdensity. As long as the overdensity is larger than 10, our worst case of field galaxy identification (50%) is sufficient to remove any uncertainty introduced by the field galaxies. And even in regions only twice as dense as the field, the remaining contamination is as little as 10% at $z = 0.1$ and 30% at $z = 0.8$! Since we can also determine the location within the cluster-box of these interlopers, we can make very precise corrections to our cluster statistics.

3.3.1. Cluster Velocity Dispersion

The peculiar velocities of galaxies in clusters can be very large, velocity dispersions of 1000–1500 km s$^{-1}$ are commonly cited in the literature. Lately, smaller values tend to be published, based on the virialized population only and where substructures have been separated, but these considerations do not apply to our study, as we are interested in infalling galaxies as well and prefer to regard a recent merger of two subclusters as one unit.

Our filters are wide enough to accommodate the red- and blueshifts introduced by these large velocities without any substantial change in colors, i.e., a genuine cluster member with a peculiar velocity of 1500 km s$^{-1}$ or even 3000 km s$^{-1}$ will not be mistakenly discarded as an interloper. The most significant difference in PC-colors between a galaxy at rest and one with a velocity of ±1500 km s$^{-1}$ is 0.0146 in PC1 for an S0 (44% of the measurement uncertainty), but typical values are much smaller, of the order of 0.004–0.012 (10%–15% of the measurement uncertainties). For a velocity of ±3000 km s$^{-1}$ these values roughly double, but such objects are much rarer. We conclude, therefore, that the width of our filters is well adapted

![Figure 9](image_url)
Fig. 10.—Differential redshift effects. Panels (a)–(c) show—for $z_{\text{obs}} = 0.1$, 0.4, and 0.7, respectively—the cluster-box and Seyfert-box boundaries, as well as the location of three representative template galaxies (E, Sb, and stb3 of Kinney et al.) in all three projections (PC1-PC2, PC2-PC3, and PC1-PC3). For each template, the tracks for $-0.1 < \delta z < +0.1$ and the intrinsic reddening vector for $A_V = 1$ are shown. Dotted lines, blueshift; dashed lines, redshift. Note how the tracks change with $z_{\text{obs}}$.  

Fig. 10a

Fig. 10b
Fig. 10.—Continued (c)

Fig. 11.—Redshift discriminating ability. Number density of visible field galaxies (solid line) as a function of $z_{\text{obs}}$ and remaining interlopers in the cluster-box (pluses) and in the Seyfert-box (crosses) for three apparent magnitude bins.
Old stellar populations are represented by G. Worthey's models (Worthey 1994). Figure 14 shows that the location of single burst populations viewed after 1 to 18 Gyr (from left to right) are consistent with the location of early-type galaxies. Only a solar metallicity burst (pluses) and a $Z/Z_\odot = -2$ model (crosses) are shown in the figure for clarity. Other subsolar metallicity bursts, or superpositions of bursts, yield similar results. We use the Starburst99 models (Leitherer et al. 1999) to model young stellar populations. The region occupied by late-type galaxies (left side of the cluster-box) can be fitted with moderately reddened bursts of star formation (Fig. 15a), as well as with continuous star formation (Fig. 15b), viewed at least 4 Myr after

http://199.120.161.183/~worthey/dial/dial_a.html.

http://www.stsci.edu/science/starburst99.

4. PHYSICAL INTERPRETATION OF THE PRINCIPAL COMPONENTS

So far, we have focused on defining the ensemble of cluster galaxies as a whole versus other objects that are likely to populate the parameter space. The next step is to "zoom in" on this ensemble, in order to characterize differences among cluster members themselves. The preceding discussion is entirely based on purely observational quantities and empirical relations. We will now show how the same quantities can be used to differentiate between different types of cluster galaxies. The aim of this section is to outline briefly the link between the PCs and the underlying physical properties of galaxies. In a follow-up publication, we will examine in greater detail the behavior of PC-colors as a function of physical properties of galaxies (age, metallicity, internal extinction, mixed stellar populations, ...) via population synthesis models.

4.1. PC1: The Hubble Sequence

The first principal component, PC1, follows essentially the Hubble sequence, from ellipticals with the highest positive values of PC1 to irregulars with the most negative PC1s. We have tested this assumption on the "normal" galaxies in our sample, i.e., the Kennicutt galaxies for which no nuclear activity or any signs of interaction with another galaxy has been detected (Fig. 13). We have relied on the NED database for morphological classification. The statistics of this sample being rather poor, as only one-third of the Kennicutt galaxies meet the above criteria, we use population synthesis models to firm up our statement.

Fig. 12.—Weakest detectable trend. Percentage of unidentified interlopers in deep cluster frames as a function of overdensity and cluster redshift from $z_{\text{cen}} = 0.1$ (lowest solid line) to $z_{\text{cen}} = 0.8$ (upper dotted line) in steps of $dz = 0.1$ (solid and dotted lines are used alternatively for clarity). In the least favorable case ($z = 0.8$, overdensity $= 2$) the remaining field contamination (after the cluster-box test) is at most 30%. Assuming a worst-case scenario, where all interlopers look alike in PC-space, any cluster galaxy property shared by more than 30% of all objects can still be detected. At $z = 0.1$, the weakest detectable trend need only be 10%, and for denser regions (at any redshift), the statistical uncertainty due to remaining interlopers will be completely negligible.

Fig. 13.—The Hubble sequence in PC-space

Fig. 14.—Models of old stellar populations (Worthey 1994). instantaneous star formation bursts with solar (pluses) and subsolar (crosses) metallicities, viewed after 1–18 Gyr of passive evolution, are consistent with the location of elliptical and S0 galaxies. Superpositions of bursts (not shown) look very similar.
Fig. 15.—Models of young stellar populations (Leitherer et al. 1999) Solar metallicity tracks with a Salpeter IMF are shown for ages from 1 to 900 Myr. 
(a) Instantaneous burst, (b) continuous star formation. $A_V = 1$ is the intrinsic reddening vector. Solid rectangle, cluster-box; dash-dotted rectangle, cluster-box with typical errors; dashed rectangle, Seyfert-box.
the initial burst. The figures show only the tracks for solar metallicity and a Salpeter initial mass function (IMF), but the situation is not much different for other metallicities and IMFs. The tracks range from 1 to 900 Myr (the age-range provided by the models), with approximate ages marked on the figures. The models lie left of the cluster-box for the first few million years. This is also the location of individual \( \text{H} \beta \) regions. We have nevertheless not extended the cluster-box to cover this region, because the unlikely chance to catch a galaxy in such a stage with large aperture photometry would be outweighed by the contamination from stars and field galaxies that this would falsely include in the cluster. Note that the models do not account for an older underlying population, which is certainly present in large aperture photometry. It is therefore not surprising that many template galaxies lie on neither of the simplistic tracks shown here. The Starburst99 models also do not account for metal enrichment or internal extinction, and are, therefore, not directly comparable to large aperture galaxy photometry. Both effects tend to make the evolutionary tracks more horizontal, under the assumption that heavy elements need to be produced (and ejected) before they start to affect the SED.

Both observations and models indicate that PC1 increases monotonically with mean stellar age. The “loop” at \( t \sim 10\text{Myr} \) in Figure 15a is an artifact of the modeling technique. Thus, PC1 is a good indicator of global star formation history. By comparing Figure 13 to Figure 10, one can see that large peculiar velocities would not alter the classification, as differential redshift effects are mainly perpendicular to PC1, and are generally small. Also shown in Figure 10 are the internal reddening vectors for \( A_V = 1 \). Note that the templates, from which the cluster-box was constructed are spatially integrated spectra of real galaxies and therefore they are already reddened by the amount of dust present in each galaxy. The vectors of “additional reddening” indicate that (a) a cluster galaxy that is unusually reddened will come to lie outside the cluster-box, but such objects can be specifically searched for (see § 3.1.2). Late-type and Seyfert galaxies, shifted by \( A_V \sim 1.5-3.0 \), would resemble the IR-luminous galaxies detected by \( \text{IRAS} \). (b) Galaxies with only slightly more reddening than is usual for their type are moved along PC1 toward earlier types.

4.2. [PC2, PC3]: Active Galactic Nuclei

It has already been hinted in § 3.1 (Fig. 5) that most galaxies with active nuclei do not fit into the cluster-box. Their total (nucleus + host) PC1 values are not much different from those of normal galaxies (slightly bluer, but we cannot determine on the basis of our sample how much of this is a real trend or due to aperture effects), but their location in the [PC2, PC3] plane is inconsistent with any kind of normal galaxy. Since the Hubble sequence is essentially parallel to PC1, any trend seen in the plane perpendicular to it will be independent of Hubble type.

Figure 16 displays all the Seyfert galaxies from the Kenicutt and Rakos samples in the [PC2, PC3] plane. The projections of the cluster-box and Seyfert-box (defined in § 3.1.2, see Fig. 5 for a three-dimensional view) are also shown. There is a clear trend with Seyfert type: Sy2’s are indistinguishable from normal galaxies, but Seyfert types 1.5 to 1 tend to lie further away from the cluster-box, mainly due to their low PC3 values, which are signatures of the nuclear flux. This trend can be interpreted in terms of inclination of the host galaxy (Antonucci 1993) determining the relative contribution of the nucleus and host galaxy stellar population to the total SED, and it is to be expected that aperture effects cause a similar trend. Thus, PC3 will not detect every active nucleus (unless the spatial resolution is good enough to permit adequate surface photometry), but it will surely identify galaxies in which the signature of nuclear activity dominates the spectrum (i.e., the object is in the Seyfert-box). Note that contamination of the Seyfert-box is very small: For most \( z_{\text{obs}} \), not even one star is likely to reside within it, and the field galaxies (see Fig. 11) are also very few (at most one, for our observations of three \( z \sim 0.2 \) clusters).

4.3. PC3: The Age-Metallicity Degeneracy

One of the major drawbacks of standard optical broad-band photometry is the age-dust-metallicity degeneracy ( Worthey 1994; Charlot, Worthey, & Bressan 1996), which can only be resolved by adding specific line indices, at high observing time cost (for the metallicity) and UV + IR bands for the dust. We found that PCA on rest-frame Strömgren photometry can resolve this degeneracy, if redshift information is independently available.

Figure 17 displays the models for old stellar populations in the [PC1, PC3] plane. In this plane, the dust reddening vector is at a large enough angle from the line formed by the various ages and metallicities, that substantial reddening can be distinguished from age and metallicity effects. The extinction by dust was calculated assuming the reddening law of Savage & Mathis (1979) and a simple intervening layer geometry. We have not used other reddening laws, such as LMC- or SMC-type laws, because they do not differ from the Milky Way law in the optical domain (Calzetti 1998). Inspection of the reddening laws produced by more complicated geometries, such as unevenly distributed,
clumpy dust (Calzetti 1997), suggests that the main difference will be only in the normalization, and not in the orientation of the reddening vector. We can thus lift the dust degeneracy in galaxy photometry, provided the nature and direction of the reddening vector. We can thus lift the dust<br>

classify AGN and galaxy statistics. We are grateful to H. Netzer for helping us with the preparation of the paper. We have shown how rest-frame photometry using intermediate-band filters, an observing technique developed by K. D. R., fills the gap between standard photometric and spectroscopic observations of galaxy clusters. The advantages of this method are the following:

1. Large fields of view can be acquired in a single telescope pointing and all sources present can be observed and analyzed simultaneously (the usual advantages of photometry).
2. The use of filters tuned to the redshift of each cluster largely overcomes the usual problem of k-corrections, allowing direct comparison of data over arbitrary large redshift ranges, without any a priori theoretical assumptions.

In this paper, we have systematized the analysis of such data using the technique of principal component analysis. We have applied PCA to synthetic colors of a StroÈmgren sample of well-known, nearby galaxies covering as much as possible all galactic properties. We demonstrated that PCA:

1. Finds the orthonormal coordinate space in which the data are most simply described. This makes it very easy to fully automate all subsequent analysis.
2. Improves and separates the information content of the data. Combined with the wise choice of the filter’s rest-frame central wavelengths, we thus gain a considerable amount of spectral information without recourse to actual spectroscopy.

Based on a training set of nearby galaxies, we have shown that we are able to:

1. Substantially reduce contamination by field stars and fore- or background galaxies;
2. Characterize the global star formation histories of cluster galaxies; and
3. Identify AGN activity of cluster members (via the Seyfert-box).

By analyzing models of stellar populations in the same manner, we have resolved the age-dust-metallicity degeneracy for old (≥1 Gyr.) stellar populations. This promises new insights on the cosmological evolution of dust and metallicity, when applied to cluster ellipticals at various redshifts. We believe that the ratio of information to observation and reduction time required for the application of this method makes it an ideal tool for cluster galaxy surveys, because it allows one to address simultaneously many evolutionary issues, such as dependence on redshift as well as on environment (cluster type, location within a cluster, . . .).

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