Young stellar populations in early-type galaxies in the Sloan Digital Sky Survey

Louisa A. Nolan,1⋆ Somak Raychaudhury1 and Ata Kabán2
1School of Physics and Astronomy, University of Birmingham, Birmingham B15 2TT
2School of Computer Science, University of Birmingham, Birmingham B15 2TT

Accepted 2006 November 20. Received 2006 November 13; in original form 2006 August 29

ABSTRACT

We use a purely data-driven rectified factor analysis to identify early-type galaxies with recent star formation in Data Release 4 of the Sloan Digital Sky Survey Spectroscopic Catalogue. We compare the spectra and environment of these galaxies with those of ‘normal’ early-type galaxies, and a sample of independently selected E+A galaxies. We calculate the projected local galaxy surface density from the nearest five and 10 neighbours (Σ5 and Σ10) for each galaxy in our sample, and find that the dependence on projected local density, of the properties of E+A galaxies, is not significantly different from that of early-type galaxies with young stellar populations, dropping off rapidly towards denser environments, and flattening off at densities Σ10 ≲ 0.1–0.3 Mpc−2. The dearth of E+A galaxies in dense environments confirms that E+A galaxies are most likely the products of galaxy–galaxy merging or interactions, rather than star-forming galaxies whose star formation has been quenched by processes unique to dense environments, such as ram-pressure stripping or galaxy harassment. We see a tentative peak in the number of E+A galaxies at Σ10 ∼ 0.1–0.3 Mpc−2, which may represent the local galaxy density at which the rate of galaxy–galaxy merging or interaction rate peaks. Analysis of the spectra of our early-type galaxies with young stellar populations suggests that they have a stellar component dominated by F stars, ∼ 1–4 Gyr old, together with a mature, metal-rich population characteristic of ‘typical’ early-type galaxies. The young stars represent ≳ 10 per cent of the stellar mass in these galaxies. This, together with the similarity of the environments in which this ‘E+F’ population and the E+A galaxy sample are found, suggests that E+F galaxies used to be E+A galaxies, but have evolved by a further ∼ one to a few Gyr. Our rectified factor analysis is sensitive enough to identify this hidden population, which allows us to study the global and intrinsic properties of early-type galaxies created in major mergers or interactions, and compare them with those early-types which have had the bulk of their stars in place since a much earlier epoch.

Key words: galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: starburst – galaxies: stellar content – cosmology: observations.

1 INTRODUCTION

There is still much uncertainty about the relative epochs of mass assembly and star formation in early-type galaxies (e.g. Cimatti, Daddi & Renzini 2006; de Lucia et al. 2006). The most massive galaxies contain the oldest stellar populations, but hierarchical structure formation requires that their present-day mass was assembled at a recent epoch. On the other hand, galaxy ‘downsizing’ (e.g. Cowie et al. 1996; Treu et al. 2005) means that less massive galaxies have more recent star formation.

One would expect that different formation histories would give rise to different observed characteristics in early-type galaxies. Several studies (e.g. Faber et al. 1997; Emsellem et al. 2004; Khochfar & Burkert 2005) have in fact found that various subclasses of early-type galaxy exist (e.g. ‘core’ and ‘cuspy’ galaxies, fast and slow rotators). We would like to know how these subclasses are related to the various modes of formation of early-type galaxies, and to the effects of their immediate environments.

The stellar populations of early-type galaxies hold the key to understanding the difference between early-types created via different evolutionary routes. If we can identify those galaxies which have recently undergone a strong starburst, and we associate that recent starburst with a major galaxy–galaxy merger or interaction,
then we can identify the products of recent merger or interaction, map their evolution with environment and redshift, and study their intrinsic properties in comparison with more massive ‘primordial’ early-types.

In this work, we are particularly interested in the relationship between E+A galaxies and ‘typical’ early-types. E+A galaxies are defined as having strong hydrogen Balmer absorption lines, but no corresponding [O II] or H{$\alpha$} emission lines. Their spectra, therefore, resemble the linear superposition of a characteristic early-type galaxy spectrum and that of an A star. This suggests that these galaxies have undergone a burst of star formation in the last Gyr or so, but that there is no ongoing star formation. It is hypothesized that these galaxies will eventually settle down as ‘normal’ passively evolving early-types.

E+A galaxies may therefore represent an intermediate stage between gas-rich, disc-dominated, rotationally supported, star-forming systems on the one hand, and bulge-dominated, pressure-supported, passive systems on the other. Hence, understanding the physical processes by which the star formation is triggered and subsequently truncated is a vital stage in understanding the evolution of early-type galaxies.

There are three possible scenarios which could explain the existence of E+A galaxies. The first is that they are in fact dust-obscured star-forming galaxies. This can be verified by observing at radio wavelengths, where star formation can be detected, but dust obscuration is not significant. Miller & Owen (2001) and Goto (2004) observed between them a total of 51 E+A galaxies. Moderate star formation was detected in only two of these galaxies, so it is unlikely that the majority of E+A are dusty starbursts.

More plausibly, then, E+A galaxies may be the product of disc–disc merging or interaction, at a stage when the starburst has burnt itself out, or they may be galaxies whose star formation has been initiated and then quenched by, for example, ram-pressure stripping or tidal stripping. The environment of these galaxies therefore holds the key to understanding them. Although, at intermediate redshift (0.33 < z < 0.83), Tran et al. (2003) find that E+As make up a non-negligible fraction (~7–13 per cent) of cluster members, suggesting a cluster-related mechanism for the truncation of star formation, such as ram-pressure or tidal stripping, at lower redshift (z ∼ 0.1), E+As appear to occur in lower-density environments, indicative of merging or interaction processes (Zabludoff et al. 1996; Blake et al. 2004).

In addition, both Zabludoff et al. (1996) and Blake et al. (2004) found a significant number of their E+A galaxies displayed tidal features and disturbed morphologies, typical of merger remnants. More recently, Goto (2005) found that E+A selected from the Sloan Digital Sky Survey (SDSS) Data Release 2 have an excess of local galaxy density only at scales of <100 kpc, and not at the scale of either clusters or larger-scale structures. This is also highly suggestive of a merger or interaction origin for E+As.

Conventional methods of identifying E+A galaxies use measurements of the equivalent width of hydrogen Balmer absorption lines (typically H{$\alpha$} and H{$\beta$}) and [O II] emission. However, this can suffer from dust obscuration of the emission lines, and emission filling of H Balmer lines, and it requires a high signal-to-noise ratio (S/N ≥ 10 pixel$^{-1}$). In addition, there has been some debate over the criteria for selecting E+A galaxies, with some authors choosing H{$\alpha$}, H{$\beta$} and [O II], with differing line strength criteria (e.g. Goto 2004, 2005), and some including H{$\gamma$} as well as H{$\alpha$}, H{$\beta$} and [O II] (e.g. Zabludoff et al. 1996; Blake et al. 2004).

Here, we use a purely data-driven rectified factor analysis data model, developed in Nolan et al. (2006), on the spectra of early-type galaxies in the SDSS Data Release 4 (DR4). This was specifically designed to exploit large data sets in a model-independent way. It uses all the data present in the spectra, i.e. the spectral features and the overall shape of the continuum, to quantify the relative strength of recent star formation in early-type galaxies extracted from the data base, in a rapid, objective and robust manner. Our method allows us to reconstruct even partial spectra, without the need to measure individual lines accurately. The advent of large surveys, such as the Sloan Digital Sky Survey allows us to study large samples of these rare objects (<1 per cent of the overall zero-redshift galaxy population, Zabludoff et al. 1996), in a way that has not been previously possible.

It has recently been shown that E+A galaxies occur more frequently at high redshift (1 ≤ z ≤ 2) compared with the local universe, at least amongst the massive red galaxy population (Doherty et al. 2005; Le Borgne et al. 2006). They may, therefore, represent a critical phase in the evolution of early-type galaxies. However, it is difficult to constrain the properties of these objects at high redshift, due to the difficulty of measuring absorption lines accurately at that redshift, and in obtaining statistically significant spectroscopic samples. Studying large samples at low redshift is therefore vital for the understanding of these objects.

In this work, we use our data modelling to identify early-type galaxies (ETGs) which have a young stellar population, suggesting that they have undergone a recent burst of star formation. We compare these galaxies with E+A galaxies, selected in a completely independent manner, and investigate the environment of our galaxy samples, in order to understand the physical mechanisms leading to the cessation of star formation.

In Section 2, we define the selection of the early-type sample, and the E+A subsample for comparison. We discuss the factor analysis of the early-type spectra that is used to reveal young stellar populations in Section 3. In Section 4, we compare our results from the analysis of early-type galaxies with the sample of E+A galaxies. In Section 5, we investigate the relationship between the galaxies in our various samples and their local environment. Our conclusions are discussed in Section 6.

2 THE SAMPLE

Our sample of early-type galaxy spectra was selected from the SDSS DR4 spectroscopic catalogue. We follow the criteria of Bernardi et al. (2003) to select early-type galaxies:

(i) the likelihood that a de Vaucouleurs profile fits the radial surface brightness distribution is at least 1.03 times the likelihood that the radial profile is exponential;
(ii) the concentration index $r_{90}/r_{50} > 2.5$ in the i-band;
(iii) the r-band Petrosian magnitude <17.5;
(iv) the photometric S/N > 4;
(v) the galaxy is not blended, de-blended or a child galaxy;
(vi) a surface brightness profile has been fitted, and it is not saturated;
(vii) redshift $z < 0.3$ and the confidence in the redshift zConf > 0.95.

We also select E+A galaxies from the SDSS DR4. Here, we use the criteria of Goto (2005), so that we can compare the results of our factor analysis of the early-type galaxy sample with their sample of E+As. The criteria are the following:

(i) H{$\alpha$} equivalent width (EW) < 3.0 Å;
where emission lines have positive values. The sample is not restricted by any morphological criteria.

This gives us a sample of over 26,000 early-type galaxy spectra, and 765 Goto E+As, which we de-redshift and re-bin at the SDSS full width at half-maximum (FWHM) spectral resolution, with the observational errors supplied re-binned correspondingly in quadrature.

In this work, we consider only those galaxies in our samples which lie in the range $0.06 < z < 0.14$. Around 50 per cent of the galaxies in our ETG sample lie within this range, and restricting ourselves to a limited redshift range minimizes any effects arising from the fixed size of the SDSS fibre diameters. At $z = 0.1$, the central $\sim 5.5$ kpc are covered, which represents 20–40 per cent of the total stellar light, which should be a good representation of the bulk stellar light. The emission lines used to select E+A galaxy spectra are measured from the same spectra that we decompose using our data model, so we are of course comparing results extracted from exactly the same region of each galaxy.

The redshift cut means that, in this work, we do not explore the evolution of ETGs with young stellar populations with redshift. However, we also need not worry about $k$-corrections to the magnitudes. The redshift range $0.06 < z < 0.14$ is less than 1 Gyr of stellar evolution; $k$-corrections would probably introduce uncertainties at least on this scale. Hence, we use a magnitude limit of $r < 17.5$ for all our samples, where $r$ is the Petrosian $r$-band magnitude. The SDSS DR4 spectroscopic catalogue is complete to this limit.

3 MODELLING THE SPECTRA

In order to analyse the spectra of our early-type galaxy sample, we model the data using the rectified factor analysis data model that we developed in Nolan et al. (2006). This model-independent technique is able to recover physically meaningful components of the observed spectra in a timely manner. Our approach and the underlying rationale for choosing the rectified factor model for modelling the data are described in detail in Nolan et al. (2006, section 4.1), along with the details of an implementation employing variational Bayesian techniques (Nolan et al. 2006, section 3.1). This modelling is an unsupervised technique, i.e. a data-driven exploratory analysis tool, designed to help us discover the underlying structure of the data and to derive features for either interpretation or subsequent quantitative analyses. Unsupervised techniques are machine-learning approaches, which do not require a priori specified targets for the training examples but instead, the data density is modelled. This model also includes latent variables that are then used to infer patterns in the data that are hoped to reveal useful relationships.

The model is first trained on half of the SDSS early-type galaxy spectra ($\sim 13,000$ galaxies), and the recovered components are then used to reconstruct the remaining ETG spectra, and the spectra in the Goto E+As sample (GE+As). Following Nolan et al. (2006, see section 4 and fig. 4), we chose to have two spectral components, which were shown to be sufficient to represent the bulk of the stars in early-type galaxies. Fig. 1 shows the two-component spectra recovered from the factor analysis, together with a 10-Gyr, 2.5 $Z_\odot$ single stellar population model (Bruzual & Charlot 2003) and a typical supersolar F star spectrum (Santos et al. 1995) for comparison. Features typical of a mature, metal-rich stellar population, a corresponding lack of evolved metal absorption lines. The second component has the characteristic shape and spectral features of a mature, metal-rich stellar population, such as those that are expected to dominate in early-type galaxies. This component has a well-developed 4000-Å break, typical of such populations. Clearly, the two components recovered represent young and old stellar contributions to the spectra of ETGs, although of course they cannot be exactly interpreted as single stellar populations. Although the second component is well fitted by the 10-Gyr stellar population, the first component is slightly redder than that of the F star. This probably reflects both a more complex star formation history than a simple two-component model, and that the ‘real’ spectrum is that of the integrated young stellar population, rather than that of a single stellar type. Ferreras et al. (2006), using a principal components analysis on the 3500–7500 Å spectra of 30 ellipticals in groups and the field, recover similar representations of old and young stellar populations in their first two components. Their results are also consistent with the representation of the bulk of stars in early-type galaxies by two components.

4 COMPARISON OF THE EARLY-TYPE GALAXIES AND THE E+AS SAMPLE

Within our chosen redshift range, we are left with 13,111 ETGs. Keeping only those galaxies in the GE+As sample which have Hα, Hβ and [O ii] securely determined leaves us with 196 GE+As. Within the ETG sample, we define a subsample of ETGs with young stellar populations (YSPEs). These are galaxies for which $A_1$, the contribution (or weight) of the ‘young’ data model component, is...
from young stars. The GE lines and a steeper 5000–8000 Å slope than the ETG spectrum. Only classified in our scheme as early-types, and those that would not.

greater than \(a_2\), the weight of the ‘old’ data model component. By comparison with stellar population models, we estimate \(a_1 > a_2\) is equivalent to an approximate lower limit to the young stellar population of \(\gtrsim 10\) per cent by stellar mass. YSPETs account for 17 per cent of the ETGs (2245 galaxies).

In Fig. 2 we plot the mean spectra for each of these three categories, with the vertical normalization adjusted for ease of comparison. The mean GE+A and YSPET spectra are very similar longwards of H\(\delta\), and both have stronger hydrogen Balmer absorption lines and a steeper 5000–8000 Å slope than the ETG spectrum. This is characteristic of the presence of contributions to the flux from young stars. The GE+A mean spectrum shows contributions from the characteristic features of even younger stars than does the YSPET mean spectrum. It has stronger hydrogen Balmer absorption lines, enhanced flux just longwards of 4000 Å, and the flux falls off more steeply towards the blue end of the spectrum shortwards of 4000 Å (see Fig. 3).

In Fig. 3, we show the likely stellar composition of the GE+A and YSPET galaxies. The E+A galaxies, as one would expect, resemble the linear combination of a mature, metal-rich stellar population (the ‘E’ component) together with a population dominated by young (~0.7 Gyr) A stars. The mean YSPET spectrum is similar, but in this case, the younger stellar component is better represented by F stars, which dominate the flux of a young stellar population at a later epoch than A stars (~1–4 Gyr). Hence, our factor analysis has allowed us to define a sample of early-type galaxies with young-intermediate aged stars, which, as F stars dominate the integrated spectrum of a stellar population for longer than the short-lived A stars, presents us with a larger sample of galaxies which have undergone recent star-forming activity than E+A samples are able to.

Furthermore, in Fig. 4, we plot the number densities of the weights of the data model components for our three classes of spectra. We have further divided the GE+A galaxies into those that would be classified in our scheme as early-types, and those that would not. Only \(\sim 17\) per cent of the GE+As (34) are typical early-type galaxies, of which two-thirds are in the \(a_1 > a_2\) region. The distribution of the GE+A is less peaked in either \(a_1\) or \(a_2\) than the YSPETs, which broadly follow the same distribution as the ETGs.

That most of the GE+A galaxies are not ETGs is consistent with the idea that they are the result of galaxy–galaxy mergers or interactions, and are at an earlier epoch in their post-merger evolution than the YSPETs. Their young stellar component is consistent with being less than 1 Gyr old. This is less than the typical time for the colours and surface brightness distributions of merger remnants to relax into those which are typical of ETGs, and which we use to identify ETGs in the SDSS catalogue. Of course, it should also be noted that if GE+As are quenched spirals, whose star formation has been recently halted by ram-pressure or tidal stripping, one would also expect them not to be classified as ETGs under our scheme.

### 5 THE ENVIRONMENTAL DEPENDENCE

In order to investigate the mechanisms via which E+As are formed, we have quantified the environment of our sample galaxies. First, we find \(\sigma_{10}\) and \(\sigma_4\), the projected distance between the galaxy and its 10th and 5th nearest neighbours in the SDSS spectroscopic catalogue. We use a Petrovian magnitude limit, \(r < 17.5\), and do not \(k\)-correct our magnitudes, due to the limited redshift range of our sample (see Section 2). The SDSS DR4 spectroscopic survey is \(\sim 92\) per cent complete (Ani Thakar, private communication), so we are able to take advantage of the spectroscopic redshifts in determining environment.

We cut in peculiar velocity at \(\pm 1000\) km s\(^{-1}\) from each galaxy, to attempt to avoid background or foreground objects, but include cluster members if the target galaxy belongs to a cluster. We have not attempted here to determine cluster membership, and a more sophisticated analysis is reserved for a later paper. Here, we are only interested in the projected local galaxy density.

The projected distances are then transformed into an estimate of the local projected surface density, \(\Sigma_{10}\) and \(\Sigma_4\). We have made a cut in \(\sigma_4\) to allow for the effects of the survey boundary, which could lead to an underestimate of local density for those galaxies in the...
low-density regions. Following Clemens et al. (2006) and Miller et al. (2003) we cut at $\sigma_{\text{max}} = 7.2$ Mpc.

In Fig. 5, the normalized number distributions of local galaxy surface density, $\Sigma_{10}$ and $\Sigma_{10}$, are shown for the YSPET and the GE+A galaxy populations. The similarities between the samples can be clearly seen. The distribution of the GE+A follows that of the YSPETs in both cases. The fraction of GE+A perhaps peaks at around $\Sigma_{10} \sim 0.1–0.3$ Mpc$^{-2}$, and both populations fall off strongly towards higher density environments. The fraction of YSPETs flattens off after this peak in $\Sigma_{10}$, and in $\Sigma_5$, the YSPET distribution is consistent with a flattening off at surface densities less than $0.2–0.3$.

Performing a Kolmogorov–Smirnov test on the GE+A and YSPET populations returns the probabilities, $(p - 1) = 4 \times 10^{-4}$ ($\Sigma_5$) and 0.3 ($\Sigma_{10}$) that the two samples are taken from different distributions. Therefore, in both cases, despite our completely independent selection procedures, the distributions of the two populations are not significantly different, consistent with the hypothesis that our YSPETs are in fact evolved E+A galaxies (E+F galaxies). The decreasing fraction of E+A and YSPETs towards increasing densities strongly argues for the hypothesis that the majority of GE+A or YSPETs are not the product of cluster-related processes (e.g. ram-pressure stripping). This confirms the result of Goto (2005) that E+A galaxies are likely to be the product of galaxy–galaxy mergers and interactions in a group environment.

Studies of star-forming galaxies of all morphologies in the SDSS and the Two Degree Field Galaxy Redshift Survey (2dFGRS) (e.g. Lewis et al. 2002; Gómez et al. 2003; Balogh et al. 2004; Poggianti et al. 2006) find that the star formation rate falls off steeply with increasing density, but converges to the field galaxy distribution at a projected density of $\sim 1$ Mpc$^{-2}$. In addition, Balogh et al. (2004) find that the fraction of star-forming galaxies of all morphologies falls steeply with respect to $\Sigma_5 \gtrsim 0.4$ Mpc$^{-2}$, flattening off at densities less than this, in good agreement with our results (see their figs 5 and 6).

The peak in fraction at $\Sigma_{10} \sim 0.1–0.3$ Mpc$^{-2}$ may indicate the optimum local galaxy surface density for galaxy–galaxy mergers and interactions, representing a trade-off between sufficient density for frequent galaxy–galaxy encounters, and slow enough relative velocities that those encounters lead to an interaction. Investigation of the results of $N$-body simulations would be able confirm or reject this. However, there is support for this argument in the recent results of Ferreras et al. (2006). They find a higher mass fraction of younger stars in some group galaxies than in the field galaxies, implying a more complex star formation history for galaxies in groups than in the field, in qualitative agreement with our tentative peak of recent starburst activity.

Further evidence for a peak in star formation with respect to local galaxy density is found by Porter & Raychaudhury (in preparation). Along filaments joining rich clusters, they find a peak in star formation at 3–4 Mpc from cluster centres. However, a careful assessment of group, cluster and filament membership is necessary, as the precise location of the peak depends upon whether a galaxy is a member of any of these environmental classes.
Many authors have found that the star formation rate begins to fall at densities $\gtrsim 1$ Mpc$^{-2}$ (e.g. Lewis et al. 2002; Gómez et al. 2003; Balogh et al. 2004; Poggianti et al. 2006; Porter & Raychaudhury, in preparation). However we find, as do Balogh et al. (2004), that the fraction of star-forming galaxies starts to fall off at lower densities (0.1–0.4 Mpc$^{-2}$), with the caveat that peaks and breaks with respect to density depend on a measurement of environment more complex than simple projected local galaxy density, as mentioned above. This is suggestive that actively star-forming disc galaxies have their (moderate compared with disc–disc merging starbursts) star formation quenched in group environments, decreasing the active-to-passive galaxy ratio. At the same time, more disc–disc merging or interaction occurs in the group environment, with associated massive star formation, keeping the star formation rate high at higher densities, whilst contributing to the fall in the number of disc galaxies. Hence, both morphological and spectroscopic data are required in order to study these different processes effectively.

6 CONCLUSIONS

We have successfully used our data-driven rectified factor analysis to identify early-type galaxies with young stellar populations, without having to apply the far more computationally expensive method of fitting detailed stellar population synthesis models to a sample of $>13000$ ETGs in the redshift range 0.06 $< z < 0.14$. We have used the sample generated as a result to map the relationship between early-type galaxies, E+A galaxies and early-type galaxies with young stellar populations. Our analysis recovers two components from the set of early-type galaxy spectra, one of which represents the contribution to the flux from mature, metal-rich stars, and the other which represents the contribution from F stars, $\sim 1–4$ Gyr old. Our method allows us to reconstruct spectra even when the observed spectra are incomplete. We do not need high-S/N measurements of individual lines. We identify those early-types which have undergone recent ($\sim 1–4$ Gyr) star formation, with the young stars accounting for at least 10 per cent of their stellar mass (YSPETs). At redshifts 0.06 $< z < 0.14$, 17 per cent of ETGs are classified as YSPETs. We propose that these YSPETs are ‘E+F’ galaxies, whose spectra are a linear combination of a typical early-type galaxy spectrum and that of an F star, analogous to E+A spectra.

We also select a sample of E+A galaxies in a completely independent way, without using the morphological criteria we used to identify early-type galaxies, but instead relying on the emission and absorption-line criteria of Goto (2005). The characteristic ‘E+A’ spectra of the Goto-selected sample, and the fact that many of these E+As do not fulfil the colour and concentration criteria for typical early-type galaxies, suggests that these galaxies are in an early ($<1$ Gyr) post galaxy–galaxy merger or interaction phase. Goto (2005) notes that most of the E+As in his sample have concentrations as high as typical ellipticals ($C_\text{e} < 0.4$), so it is likely that many of these galaxies are not included in our early-type sample because they are too blue, indicating that massive (A star and earlier) stars are still burning. If E+As are recently quenched star-forming galaxies, we would expect them to be located preferentially in dense cluster regions, whereas we see the majority residing in field or group environments, and the number falls off towards denser environments, in agreement with Goto’s result. Their high concentrations and preferentially low-density environments argue strongly that these are the products of galaxy–galaxy mergers or interactions, which will eventually settle down to become typical early-type galaxies.

We note that there is in fact a slight peak in the local galaxy surface density distribution of E+A galaxies at 0.1–0.3 Mpc$^{-2}$. This may represent the optimum local galaxy surface density for galaxy–galaxy mergers and interactions. Realistic cosmological simulations should be able to confirm or reject this hypothesis.

Given that the distribution of local galaxy surface density of the GE+A galaxies and that of the independently determined YSPET populations are not significantly different, one might expect a similar history for both sets of galaxies. We hypothesize that the YSPETs, with typical ETG colours and concentrations, and ‘E+F’ spectra, represent an intermediate evolutionary stage between E+As and early-types. As this is a longer-lived stage than E+A galaxies (F stars persist on the main sequence for longer than A stars, and dominate the integrated flux at ages $\lesssim 5$ Gyr), we are able to identify a larger sample of these galaxies than is possible with the very rare E+As. We therefore have identified a powerful tool for studying in detail, both globally and individually, the evolution of early-type galaxies.

Our future work will compare the dependence on local density of E+A and E+F galaxies that we have recovered here, with those recovered from simulations. We intend to perform the same analysis on 2dFGRS galaxies and a sample of high-redshift galaxies for comparison. We also intend to investigate the relationship between E+A and E+F galaxies by studying their kinematics in detail using integral field spectroscopy.

ACKNOWLEDGMENTS

Thanks to Ani Thakar at the SDSS helpdesk for valuable assistance with the SDSS archive. Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the US Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society and the Higher Education Funding Council for England. The SDSS Web Site is http://www.sdss.org/.

REFERENCES

Balogh M. et al., 2004, MNRAS, 348, 1355
Bernardi M. et al., 2003, AJ, 125, 1817
Blake C. et al., 2004, MNRAS, 355, 713
Bruzual G., Charlot S., 2003, MNRAS, 344, 1000
Cimatti A., Daddi E., Renzini A., 2006, A&A, 453, L29
Clemens M. S., Bressan A., Nikolic B., Alexander P., Annibali F., Rampazzo R., 2006, MNRAS, 370, 702
Cowie L. L., Songaila A., Hu E. M., Cohen J. G., 1996, AJ, 112, 839
de Lucia G., Springel V., White S. D. M., Croton D., Kauffmann G., 2006, MNRAS, 366, 499
Doherty M., Bunker A. J., Ellis R. S., McCarthy P. J., 2005, MNRAS, 361, 525
Emselflem E. et al., 2004, MNRAS, 352, 721
Faber S. M. et al., 1997, AJ, 114, 1771
Ferreras I., Pasquali A., de Carvalho R. R., de la Rosa I. G., Lahav O., 2006, MNRAS, 370, 828
Gómez P. L. et al., 2003, ApJ, 584, 210
Goto T., 2004, A&A, 427, 125
Goto T., 2005, MNRAS, 357, 937
Khochfar S., Burkert A., 2005, MNRAS, 359, 1379
Kurucz R. L., 1993, VizieR Online Data Catalog, 6039, 0
Le Borgne D. et al., 2006, ApJ, 642, 48
Lewis I. et al., 2002, MNRAS, 334, 673
Miller C. J., Nichol R. C., Gómez P. L., Hopkins A. M., Bernardi M., 2003, ApJ, 597, 142
Miller N. A., Owen F. N., 2001, ApJ, 554, L25
YSPs in ETGs in the SDSS

Nolan L. A., Harva M. O., Kabán A., Raychaudhury S., 2006, MNRAS, 366, 321
Poggianti B. M. et al., 2006, ApJ, 642, 188
Santos J. F. C. Jr., Bica E., Dottori H., Ortolani S., Barbuy B., 1995, A&A, 303, 753
Tran K.-V. H., Franx M., Illingworth G., Kelson D. D., van Dokkum P., 2003, ApJ, 599, 865
Treu T., Ellis R. S., Liao T. X., van Dokkum P. G., 2005, ApJ, 622, L5
Zabludoff A. I., Zaritsky D., Lin H., Tucker D., Hashimoto Y., Shectman S. A., Oemler A., Kirshner R. P., 1996, ApJ, 466, 104

This paper has been typeset from a TeX/LaTeX file prepared by the author.