

Bursty stellar populations and obscured AGN in galaxy bulges

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ABSTRACT

We investigate trends between the recent star formation history and black hole growth in galaxy bulges in the Sloan Digital Sky Survey (SDSS). The galaxies lie at $0.01 < z < 0.07$ where the fibre aperture covers only the central 0.6–4.0 kpc diameter of the galaxy. We find strong trends between black hole growth, as measured by dust-attenuation-corrected [O III] luminosity, and the recent star formation history of the bulges. 56% of the bulges are quiescent with no signs of recent or ongoing star formation and, while almost half of all AGN lie within these bulges, they contribute only $\sim 10\%$ to the total black hole growth in the local Universe. At the other extreme, the AGN contained within the $\sim 4\%$ of galaxy bulges that are undergoing or have recently undergone the strongest starbursts, contribute at least 10–20% of the total black hole growth. Much of this growth occurs in AGN with high amounts of dust extinction and thus the precise numbers remain uncertain. The remainder of the black hole growth ($>60\%$) is contributed by bulges with more moderate recent or ongoing star formation. The strongest accreting black holes reside in bulges with a wide range in recent SFH. We conclude that our results support the popular hypothesis for black hole growth occurring through gas inflow into the central regions of galaxies, followed by a starburst and triggering of the AGN. However, while this is a significant pathway for the growth of black holes, it is not the dominant one in the present-day Universe. More unspectacular processes are apparently responsible for the majority of this growth.

In order to arrive at these conclusions we have developed a set of new high signal-to-noise ratio (SNR) optical spectral indicators, designed to allow a detailed study of stellar populations which have undergone recent enhanced star formation. Working in the rest-frame wavelength range 3750–4150 Å, ideally suited to many recent and ongoing spectroscopic surveys at low and high redshift, the first two indices are equivalent to the previously well studied 4000 Å break strength and H δ equivalent width. The primary advantage of this new method is a greatly improved SNR for the latter index, allowing the present study to use spectra with SNR-per-pixel as low as 8. The third index measures the excess strength of Ca II (H&K), which is particularly sensitive to the transition of a post-starburst spectrum from A to F stars, and allows the degeneracy between time of burst and strength of burst to be broken.

Key words: galaxies:bulges, active, stellar content; methods:statistical

1 INTRODUCTION

Galaxy spectra contain a wealth of information on the present and past star formation of galaxies, in the form of stellar continuum shape, stellar and interstellar absorption, and nebular emission lines. In particular, the region around the 4000 Å break provides us

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with powerful diagnostics of the luminosity-weighted mean stellar age and the fraction of stars formed in recent ($\lesssim 1$ Gyr) bursts, from the height of the break and the relative strength of the hydrogen Balmer absorption lines respectively. While considerable progress has been made in extracting the global star formation history (SFH) of galaxies from their present day integrated optical spectra (Kauffmann et al. 2003b; Panter et al. 2003; Ocvirk et al. 2006; Cid Fernandes et al. 2006), the potential for recovering detailed *recent* SFHs from spectra in these large datasets has remained relatively unexplored.

Determining the recent ($\lesssim 1$ Gyr) star formation history of galaxies has considerable importance for understanding the effects of external and internal physical processes on the evolution of galaxies, since this timescale corresponds to only a few galaxy dynamical times. As a result of such processes, galaxies are expected to undergo strong fluctuations in their star formation over short timescales, which may in turn be linked to other aspects of galaxy evolution, such as the build-up of stellar bulges.

Sharp transitions in the star formation rate of galaxies leave clear imprints on the integrated light of the stellar population, as the balance of light contributed by stars of different masses changes. Spectroscopic research in this area has focussed in particular on so-called E+A (or K+A) galaxies – an early type galaxy spectrum and superposed A-type stellar spectrum, resulting in strong Balmer absorption lines. An excess population of A stars results when the corresponding O and B star population, which dominates the light during ongoing star formation, has died out or is not visible. Therefore, the relative fraction of A to O stars provides information on changes in the star formation rate of galaxies over the last ~ 1 –2 Gyr.

Studied spectroscopically since the early 1980’s, these objects have been suggested to be caused by either a short burst of star formation in the last Gyr (Sparke et al. 1980; Dressler & Gunn 1983; Dressler et al. 2004; Nolan et al. 2006), recent truncation of star formation caused by stripping of gas in cluster environments (Poggianti et al. 1999, 2004), or simply obscuration of younger, hotter stars by dust (Smail et al. 1999; Miller & Owen 2001; Poggianti & Wu 2000). All these scenarios may contribute to the E+A galaxy population (see also Hogg et al. 2006), although it is generally believed that the objects with very strong Balmer absorption lines are incompatible with pure truncation of star formation and are likely to be true “post-starburst” objects (Balogh et al. 2005).

The E+A phenomena is also often observationally linked with the presence of an AGN (Kauffmann et al. 2003a; Cid Fernandes et al. 2004; Tadhunter et al. 2005; Bender et al. 2005; Goto 2006; Yip et al. 2004; Yan et al. 2006), with direct implications for the starburst-AGN connection; it is this question which we primarily aim to address in this paper. Recent numerical simulations have suggested a scenario in which major mergers between galaxies provide the fuel and a disrupted gravitational potential conducive to both the build up of the galaxy bulge through star formation and the fuelling of the central black hole. Di Matteo et al. (2005) and Hopkins et al. (2006) suggest that triggering by such major mergers can account for the properties of the entire QSO population. Direct observational confirmation of this scenario remains elusive however, and the causal connection between starburst and AGN activity is still unconstrained. Furthermore, alternative theories for the build up of black hole mass in a less spectacular fashion do exist (e.g. King & Pringle 2007). To be able to accurately describe the recent SFH of galaxies, in terms of the age and strength of recent starbursts, and to distinguish between

truncation of star formation, starbursts or starbursts followed by truncation, will allow such theoretical scenarios to be thoroughly tested.

Our ability to measure recent fluctuations in the star formation rate of galaxies has in part been restricted by the high signal-to-noise ratio (SNR) required of spectra in order to measure the H δ Balmer line with accuracy. The H δ line is important as the strongest Balmer absorption line not to suffer irreparably from emission line infilling in all but the galaxies with the highest star formation rates. However, this traditional diagnostic is no longer adequate for our purposes, being unsuitable for detecting all but the strongest post-starburst galaxies in current high redshift spectroscopic surveys, or for detecting small and/or relatively old bursts without employing the stacking spectra to obtain mean results (Dressler et al. 2004). The intrinsic dependence of the H δ line strength on luminosity weighted mean stellar age also causes populations defined through a simple cut on equivalent width (EW) to be biased towards the youngest or the very strongest post-starburst systems. For these reasons we develop in this paper a new set of spectral indicators specifically designed to quantify the recent star formation of galaxies. These new indicators are based on a Principal Component Analysis (PCA) of the spectral region 3750–4150Å of a set of model galaxies created from the Bruzual & Charlot (2003, hereafter BC03) GALAXEV spectral synthesis code, a proportion of which have undergone stochastic starbursts. PCA is traditionally used to identify correlations and variance in datasets and has often been applied to galaxy spectra (Connolly et al. 1995; Glazebrook et al. 1998; Madgwick et al. 2002, 2003; Yip et al. 2004; Ferreras et al. 2006). By applying PCA to spectral data, collections of correlated features, such as the Balmer absorption lines, are easily extracted and quantified as a single parameter. Allowing all Balmer absorption lines to contribute to measuring the Balmer absorption strength greatly improves over the SNR obtained from measuring a single line alone.

As we shall show, the first three principal components output from our analysis are easily interpreted as: 1) 4000Å break strength (correlated with Balmer absorption line strength); 2) *excess* Balmer absorption; 3) *excess* Ca II (H&K) absorption. Previous work has made extensive use of $D_n(4000)$ and H δ line strength to recover underlying physical parameters of galaxies in the Sloan Digital Sky Survey (SDSS) such as stellar mass and age (e.g. Kauffmann et al. 2003b), and the first two principal components simply measure the two features already known to vary most in this spectral region. The third component, Ca II (H&K) strength, is used less often as a SFH indicator. However, it has been identified previously as a powerful diagnostic of A to F star fractions in galaxies (Rose 1985) and for breaking the degeneracy between age and strength of a recent starburst (Leonardi & Rose 1996, 2003).

In this paper we focus on the method and the qualitative trends of AGN properties with recent star formation history of their host bulges. In future papers we will use the new method to derive quantitative parameters such as starburst strengths and ages. The outline of the paper is as follows. In Section 2 we introduce the SDSS galaxy sample to which we will be applying our new method. Readers with no further interest in the method may skip to Section 7. In Section 3 the new method is presented in detail, including details of the input models, the PCA method and the physical interpretation of the resulting eigenspectra. The new indices are applied to the SDSS dataset in Section 4 and related to traditional indices to allow an easy reference point for interpretation. Duplicate observations of SDSS galaxies are used to show the improvement of our new indices over the old ones. In Section 5 we compare BC03 stel-

lar population model tracks to our sample of SDSS galaxies and provide a simple toy model with which to visualise the evolution of the galaxies in the principal component planes. In Section 6 the BC03 models are used to investigate potential biases and degeneracies involved in the interpretation of the new indices. In Section 7 we investigate trends of recent star formation history in the bulges of high surface mass density galaxies with global galaxy morphology, dust content and AGN strength. The contribution of AGN hosted by each class of bulge to the overall present day black hole accretion rate is presented. Our results are discussed in Section 8.

Where necessary we assume the standard cosmology with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ and $h = 0.7$. *Vacuum wavelengths are quoted throughout.*

2 THE SDSS GALAXY SAMPLE

The Sloan Digital Sky Survey (SDSS) spectroscopic galaxy catalogue, with more than 500 000 spectra in its fourth data release (DR4, Adelman-McCarthy et al. 2006), provides the ideal database for a first application and full testing of any new spectral analysis method. We concentrate on the bulges of low redshift galaxies. With 3" diameter fibres, the SDSS spectra probe only the central few kpc of low redshift galaxies: 0.6 - 4 kpc diameters for $0.01 < z < 0.07$. We use this "fibre aperture effect" to our advantage to allow us to study the recent star formation history of galaxy bulges close to the central active galactic nucleus (AGN) that is present in many of these systems.

Our sample is selected to be spectroscopically confirmed galaxies in the redshift range $0.01 < z < 0.07$. The upper redshift limit of 0.07 fits well with the characteristic radius of bulge-dominated galaxies in the SDSS of ~ 4.4 kpc (Bernardi et al. 2003). We further restrict the galaxies to have stellar surface mass densities ($\mu_z^* = 0.5M_{*,z}/\pi \times R_{50,z}^2$) greater than $3 \times 10^8 M_\odot \text{ kpc}^{-2}$, where M^* is stellar mass measured by Kauffmann et al. (2003c) and $R_{50,z}$ is z -band half-light Petrosian radius. Below this surface density, the disk dominates the light and the measured velocity dispersion within the fibre aperture does not relate to the central velocity dispersion of the stars around the black hole and thus cannot be used to determine black hole mass (Kauffmann et al. 2003c). We expect this cut to have minimal impact on our final analysis of total [O III] luminosities of AGN hosted by each type of stellar population, as low surface density systems contribute very little to the volume-averaged integrals of black hole mass and accretion rates (Heckman et al. 2004). A lower limit on velocity dispersion is set at 70 km s^{-1} , because the spectral resolution of the SDSS means that reliable velocity dispersions cannot be obtained for lower values. 70 km s^{-1} corresponds to a black hole mass of $10^{6.3} M_\odot$ using the observed correlation between bulge velocity dispersion and black hole mass of Tremaine et al. (2002).

To summarise, our sample contains SDSS DR4 main sample galaxies that match the following criteria:

- Spectroscopically classified as a galaxy
- With matches in the photometric catalogue
- Zwarning flag = 0
- Redshift $0.01 < z < 0.07$
- Stellar surface density $\mu_z^* > 3 \times 10^8 M_\odot \text{ kpc}^{-2}$ (M_* from Kauffmann et al. 2003b)
- Velocity dispersion $> 70 \text{ km s}^{-1}$ and velocity dispersion measured at $> 3\sigma$ significance
- Spectral SNR in the g -band $\text{SNR}_g > 8$

This results in 33913 galaxies. A further 399 galaxies with extended regions of bad pixels in the region of interest are removed from the sample leaving 33514 galaxies. Photometric properties used in this paper are taken directly from the SDSS catalogue; spectroscopic continuum parameters used, such as $H\delta_\Lambda$ and $D_n(4000)$, are available through the SDSS-MPA value added catalogue webpages¹ and described in Tremonti et al. (2004).

Because we are interested in the average properties of different types of galaxies within our sample, it is important to allow for the fact that the sample is magnitude- and not volume-limited. We do this by weighting each galaxy contributing to a mean or total quantity by $1/V_{\text{max}}$, where V_{max} is the maximum volume in which the galaxy may be observed in the spectroscopic survey (Schmidt 1968).

2.1 Emission line analysis of SDSS spectra

We use the Baldwin et al. (1981, BPT) method to discriminate between narrow emission lines that are primarily caused by ongoing star formation or a central AGN, using the flux ratios $[N \text{ II}]/H\alpha$ and $[O \text{ III}]/H\beta$. The sample is divided into four primary sub-samples: 'pure AGN' (3165), AGN including composite objects (AGN+composite, 11751), star forming (SF, 6357) and unclassified objects (unclass, 15406). The emission line ratios of pure-AGN place them above the stringent theoretical criterion of Kewley et al. (2001):

$$\log([O \text{ III}]/H\beta) > 0.61/\log([N \text{ II}]/H\alpha) - 0.47 + 1.19 \quad (1)$$

with all 4 lines detected at $> 3\sigma$ or, if $H\beta$ is too weak to reach the requisite SNR, the $[N \text{ II}]/H\alpha$ flux ratio is greater than 0.2. The 'AGN+composite' sample has emission lines that lie above the observationally determined demarcation line of Kauffmann et al. (2003a):

$$\log([O \text{ III}]/H\beta) > 0.61/\log([N \text{ II}]/H\alpha) - 0.05 + 1.3 \quad (2)$$

or have $[N \text{ II}]/H\alpha$ flux ratio greater than -0.2 . Non-AGN have lines that are dominated by star formation. The remainder are 'unclassified', primarily because of non-existent or very weak emission lines.

The emission line measurements are provided on the SDSS-MPA webpages and details are given in Brinchmann et al. (2004); errors have been rescaled according to the information provided on the website. Briefly, spectral synthesis models are used to fit the stellar continuum, including absorption features, and emission lines are measured from the residual of the data and model fit, thus contamination of the nebular emission lines by stellar absorption is accounted for.

2.1.1 Correction for dust attenuation

Dust attenuation of the emission lines is corrected for when $H\alpha$ and $H\beta$ are measured with SNR of $> 3\sigma$ and the flux in the $H\beta$ line is greater than $4 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$, using the Balmer decrement method. The latter cut on $H\beta$ flux was placed after investigation of objects with very high balmer decrements, which were often found to have apparently underestimated errors on $H\beta$. We assume an intrinsic Case B ratio of 2.87 (Osterbrock 1989). We note that a slightly higher ratio of ~ 3 is generally accepted to apply in AGN,

¹ <http://www.mpa-garching.mpg.de/SDSS/>

and this will cause a small systematic overestimate of our dust attenuations where emission lines are dominated by AGN (of $\sim 15\%$ at [O III]). However, separating the relative contributions of star formation and AGN to the lines is a difficult topic and we use a single ratio for simplicity.

The form of the dust attenuation in star forming regions (birth clouds) and narrow line regions around AGN is not well known, but has a significant impact on our results. We therefore choose to present our results using two different attenuation corrections. The first is a single power-law of the form $\tau_\lambda \propto \lambda^{-0.7}$ which provides a good fit to the UV to IR continua of starburst galaxies (Charlot & Fall 2000). However, the attenuation caused by the birth clouds from which the emission lines originate will be more screen like (less grey) in form and this is not accounted for in the simple single-power law prescription. This results in dust-corrected [O III] emission line luminosities in average starforming galaxies that are a factor of several higher than those derived using a standard Milky-Way like absorption curve. We therefore introduce a second prescription, designed *specifically for the purposes of correcting emission lines*:

$$\frac{\tau_\lambda}{\tau_V} = (1 - \mu) \left(\frac{\lambda}{5500\text{\AA}} \right)^{-1.3} + \mu \left(\frac{\lambda}{5500\text{\AA}} \right)^{-0.7} \quad (3)$$

where τ_V is the total effective optical depth in the V -band and μ is the fraction of total τ_V caused by the ambient ISM. We set $\mu = 0.3$ based on observed relations between UV continuum slope and $H\alpha$ to $H\beta$ emission line ratios. Although the exponent in the first term is not well constrained by observations of external galaxies, -1.3 lies between that observed in line-of-sight observations to stars in the Milky Way, LMC and SMC (Charlot & Fall 2000). This new dust prescription thus accounts for the attenuation of the emission lines within the birth clouds (first term) and the attenuation as the light passes through the ISM [second term, see da Cunha et al. (in preparation) for further details].

Due primarily to insufficient SNR of the weaker $H\beta$ emission line, it is only possible to correct 26% of our galaxies for dust attenuation of the emission lines. The majority of the objects without dust attenuation corrections are quiescent systems with little ongoing star formation and thus very weak emission lines; this accounts for 73% of the galaxies we are unable to calculate corrections for, using the classification of Section 7.1. These old stellar populations are known to contain very low quantities of dust: we find they have mean z -band attenuations consistent with zero (derived from model fits to the stellar continuum by Kauffmann et al. (2003b)). As the star formation rate of systems increases, the percentage that we can correct for dust attenuation rises, as does their mean dust content. For the galaxy-bulges with normal levels of ongoing star formation (mean log specific star formation within the fibre of -10.26 , see Section 7.1), 68% are corrected for dust attenuation and for the starbursting galaxies 98% are corrected. We therefore believe that the primary results of this paper are not biased by the objects for which dust attenuation correction of the emission lines is not possible. However, as will be discussed later, there is a population of objects for which it is likely that we are unable to measure $H\beta$ in a large fraction due to extreme dust attenuation. While this bias has been included in our discussions where appropriate, we note that these systems account for only $\sim 1.5\%$ of those for which a Balmer decrement is not obtained.

2.2 Stellar populations of broad line AGN

Our galaxy sample has been specifically selected to omit broad line (Type 1) AGN. This is achieved by an automated spectroscopic classification algorithm within the standard SDSS pipeline. Uncovering the true stellar populations of broad line AGN is a substantial topic in its own right, due to the contamination of the stellar light by continuum light from the AGN. We have made no attempt in this paper to study broad line AGN, and refer the interested reader to Kauffmann et al. (2003a), Hao et al. (2005), and Yip et al. (2004) for studies of their stellar populations and contribution to the [O III] luminosity density in the SDSS. Within the unified model of AGN, Type 1 (broad line, unobscured) and Type 2 (narrow line, obscured) AGN are expected to differ only in the sightline by which they are viewed. In this scenario the stellar populations of Type 2 AGN are expected to be representative of those of Type 1 AGN with the same [O III] luminosities. This was the conclusion arrived at by Kauffmann et al. (2003a) and, while the precise balance of stellar population classes as derived in this paper of Type 1 AGN relative to Type 2 AGN is obviously of great interest, it is beyond the scope of the present paper.

3 METHOD: BUILDING THE NEW INDICES

Our primary goal is to improve upon the traditional method of identifying post-starburst galaxies through the strength of $H\delta$ absorption and [O II] emission. We therefore concentrate on the Balmer line region of the galaxy continuum, which, in the optical, contains the greatest amount of information on the relative fractions of O to A stars. By selecting a small wavelength region, we also minimise the effects of internal dust attenuation in the galaxies, and can easily uncover and isolate discrepancies between models and data.

In Figure 1 a selection of stellar spectra are plotted in the wavelength range 3750–4200Å. The defining wavelength regions of two indices traditionally applied in this region are indicated and prominent absorption lines marked. With decreasing stellar temperature the 4000Å break strength [as measured by $D_n(4000)$] increases and the $H\delta$ $\lambda 4102.9$ absorption line first strengthens and then weakens. A strong UV continuum is evident in the hottest stars. Each stellar type has a characteristic main sequence lifetime, ~ 0.5 Gyr and 3 Gyr for A and F stars respectively; it is these different lifetimes that allow us to study the star formation histories of stellar populations. Ca II (H&K) strength increases rapidly through A stars to F stars, the ratio of Ca II(H)+He to Ca II(K) thus provides the decisive fine age indicator for young ($\lesssim 1$ Gyr) stellar populations (Leonardi & Rose 1996).

The main principle behind our method is to use all the spectral features in the wavelength region around the 4000Å break, to quantify the young stellar content of the galaxy based on continuum shape and absorption line strengths. We achieve this by searching for patterns of pixels which vary most within a set of model spectra and, from these patterns, defining three new spectral indices. From previous work on galaxy spectra we expect the main variation in this wavelength range to be the strength of the 4000Å break which is well known to be a powerful stellar age indicator. The second variation is expected to be related to $H\delta$ absorption strength, which gives an additional constraint on the relative amount of any additional young stellar component. Although our original aim was simply to create a high SNR replacement for $H\delta$, our procedure also identified Ca II as a clearly interpretable third axis of variation.

The method is based on a principal component analysis

is distributed logarithmically between 0.0 and 0.1 and the length of the burst is distributed uniformly between 0.03 and 0.3 Gyr. Finally, the fraction of galaxies with *ongoing* starbursts is reduced to 25% of those initially created leaving 6473 model galaxies, 29% of which have experienced a burst in the past 2 Gyr. The number of galaxies with ongoing starbursts was reduced because the starburst features were found to overly dominate the principal components for our requirements.

It is important to be clear about the effect of the input sample on any PCA. PCA is a non-robust variance based technique: changing the distribution of input galaxies greatly affects the output principal components. Additionally, PCA is affected by outliers in the dataset, and if principal components representative of the majority of the dataset are required then such outliers must be removed. Although we set out to recreate a population of early-type galaxies with varying degrees of recent “bursty” SFHs, the details of the input sample were selected through trial and error, with the aim of recovering principal components with good power to distinguish the age and strength of recent bursts. Once the components are created, the precise details of the input set become irrelevant, simply affecting the ability of the new indices to measure the physical parameters we are interested in. We note that a more elegant way to achieve similar results may be through application of a method similar to the MOPED algorithm of Heavens et al. (2000), to tailor the principal components from the outset to the parameters we wish to extract from the data. This algorithm has already been used to derive global star formation histories and metallicities from SDSS galaxy spectra (Panter et al. 2003). At this stage however we prefer the more transparent approach of PCA, through which it is relatively straightforward to understand our results and isolate imperfections in the theoretical models. A PCA on the SDSS data was also performed and, with suitable masking of emission lines, found to produce qualitatively similar first and second principal components.

3.2 Creating the “eigenspectra”

In this and the following sections we explicitly refer to the SDSS dataset which is studied in this paper (Section 2), however the procedure may be adapted to any other dataset. The 3750–4150 Å wavelength range is extracted from the BC03 model galaxy spectra, the spectra are shifted to vacuum wavelengths, rebinned to match the logarithmic SDSS wavelength binning, and convolved to have velocity dispersions equal to 150 km s^{-1} , the mean value of the dataset to which the new indices will be applied in this paper. The effect of velocity dispersion on the derived components will be discussed further in Section 6, at this stage it suffices to note that the Balmer series lines in which we are particularly interested are strongly pressure broadened in main sequence dwarf stars, and thus in young and intermediate age stellar populations these particular line widths are relatively unaffected by the velocity dispersion of the galaxy.

Each model spectrum is normalised to have total flux of unity, the mean spectrum of the input dataset is calculated and subtracted³, and the PCA is run to produce the principal components,

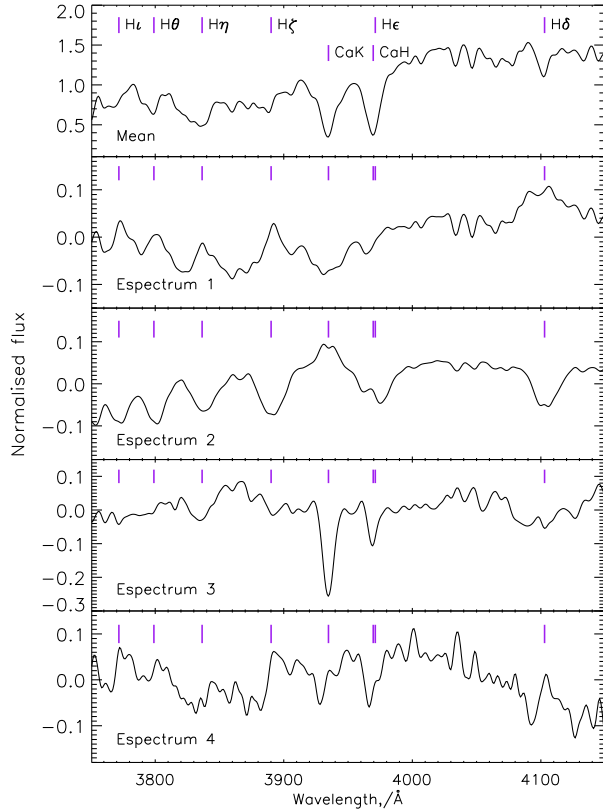


Figure 2. The eigenspectra: our new indices describe the amount of each eigenspectrum in a galaxy spectrum. The top spectrum is the “mean” spectrum of the input dataset and the eigenspectra are ordered by the amount of variance within the dataset that they account for. The main absorption features in this wavelength range, the Balmer and Ca II lines, are marked. The first eigenspectrum measures the 4000 Å break strength and anti-correlated Balmer absorption line strength. The second eigenspectrum measures a decrease in Balmer absorption and corresponding increase in the strong blue continuum of hot stars. The third eigenspectrum primarily measures any additional Ca II (H&K) absorption.

termed eigenspectra from now on, which are to define our new spectral indices.

3.3 The new indices

Figure 2 presents the mean spectrum and first four eigenspectra of our input model galaxies. The mean spectrum is typical for that of an quiescent galaxy (see Figure 10); the first component shows the 4000 Å break and corresponding inverse-correlation with Balmer line strength; the second component shows the Balmer series and inverse-correlation with the blue continuum shape seen in O and B type stars; the third component is primarily dominated by the Ca II (H&K) absorption lines, with Ca II (H) decorrelated from the broader Hε at the same wavelength; the fourth component contains further metallicity information, however, by this stage it becomes more difficult to find simple interpretations for the eigenspectra.

to lie orthogonal to the mean spectrum. Consequently, they will not properly describe the true lines of variance in the dataset. Note the purposeful difference in terminology between the *mean* spectrum of the dataset and the *normalisation* of individual spectra.

³ The subtraction of the mean spectrum from a dataset prior to a principal component analysis is an important detail, acting in exactly the same way as removing the mean before calculating the scatter in a set of numbers. Failure to do so imposes an approximate mean spectrum as the first component, and thus an unnecessary constraint on the remaining principal components

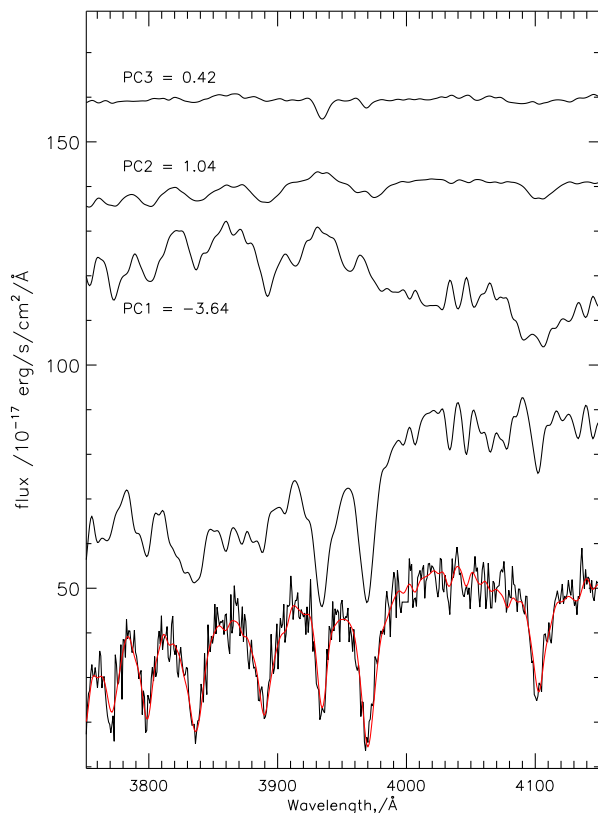


Figure 3. A galaxy with a strong A/F star component (bottom, black) is built up of the mean spectrum (second from bottom), plus given amounts (amplitudes) of the first three eigenspectra. Note that these are offset in the figure by an arbitrary flux for clarity. The amplitudes are the new indices. The resulting spectrum reconstruction (addition of the mean and the 3 eigenspectra multiplied by the amplitudes) is overplotted in red.

4 APPLICATION TO REAL DATA

The basic procedure for measuring the indices in real data is straightforward: the galaxy spectrum is corrected for foreground Galactic extinction, moved to the rest frame, the mean spectrum of the *input* (i.e. *BC03 model*) sample is subtracted, and the residual spectrum is projected onto the eigenspectra (i.e. the inner, or dot, product is calculated, see Appendix A). The resulting principal component amplitudes represent the amount of each eigenspectrum present in the galaxy spectrum; these are our new indices.

Often there are regions of a real spectrum which we do not wish to include in the analysis, for example, regions with bad sky line subtraction or regions affected by nebular emission lines. We mask these pixels with a process called Gappy-PCA, introduced to spectral analysis in astronomy by Connolly & Szalay (1999). This allows pixels to contribute zero weight during the calculation of the principal component amplitudes, although at the price that the independence of the individual components is degraded. In the SDSS dataset bad pixels are identified as those with error set to zero. Additionally we mask 5 Å either side of the Ne III λ 3870 line in spectra in which this line is detected at greater than 1.5σ , and the centers of the H δ through H10 lines in spectra with equivalent width of H δ in emission measured to be greater than 1 Å by Brinchmann et al. (2004). The effect of emission line infilling is discussed further in Section 6.2. Because the Balmer emission lines sit at the center of absorption lines, the resulting flux normalisation is systematically

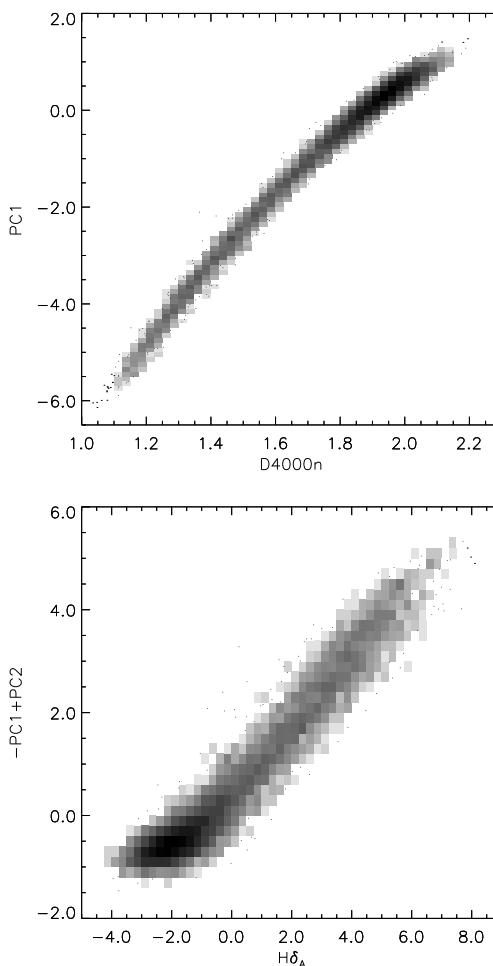


Figure 4. The relation of the new spectral indices to traditional, well studied, indices for SDSS galaxies. The dataset, described in Section 2, contains low redshift, high stellar surface mass density SDSS galaxies. For these plots only, due to the large errors on the measurement of $H\delta_A$ in noisy spectra, galaxy spectra are required to have a per pixel SNR in the *g*-band greater than 20.

biased by the masking procedure. A new Gappy-PCA algorithm has been developed by one of us (GL) which allows the flux normalisation as an additional free parameter during the calculation of the principal components⁴. This new procedure was applied to all spectra.

Figure 3 shows how a galaxy spectrum with a dominant A star population may be constructed from the mean spectrum and differing amounts (amplitudes) of the first three eigenspectrum.

It is very important to compare our new indices to the traditional indices we wish to replace in order to quickly develop a full understanding of the information they contain. Figure 4 compares the amplitudes of the first two components, PC1 and PC2, to $D_n(4000)$ (4000 Å break strength) and $H\delta_A$ (Lick index primarily describing H δ equivalent width) for the SDSS spectra presented in Section 2. We can see that PC1 is equivalent to $D_n(4000)$ with a slight curve in the relation in the sense that the PC1 axis is stretched

⁴ The IDL code and documentation for the NormGappy-PCA procedure will be available on acceptance of the paper at <http://www.voservices.net/spectrum/>.

slightly for later type galaxies compared to early type galaxies. $-\text{PC1}+\text{PC2}$ is equivalent to $\text{H}\delta_{\text{A}}$ for late type galaxies, but saturates in the early type galaxies. Note that PC2 alone is not equivalent to $\text{H}\delta_{\text{A}}$, but to *excess* $\text{H}\delta_{\text{A}}$ over that expected for the galaxy's $\text{D}_n(4000)$ value.

4.1 Improvement over old indices

The simplest way to show the improvement of our new Balmer series index over the traditional $\text{H}\delta_{\text{A}}$ measure, and therefore the benefit of developing this relatively complex technique, is to compare the indices measured from duplicate observations of the same object. Many such observations exist within the SDSS survey, from entire plates which were re-observed and also objects observed on two different plates, due to plate overlaps. A list of duplicate galaxies in SDSS DR4 has been compiled and is available on the SDSS-MPA web pages. Figures 5 and 6 compare the scatter between duplicate observations of $\text{D}_n(4000)$ and PC1, and $\text{H}\delta_{\text{A}}$ and $-\text{PC1}+\text{PC2}$, as a function of observed frame g -band SNR per pixel in both spectra. The improvement is clear, particularly for $\text{H}\delta_{\text{A}}$, although it should be recognised that $-\text{PC1}+\text{PC2}$ is not a measure of absorption line strength alone: information contained in continuum shape is also used.

5 COMPARING MODELS AND DATA

In the top-left panel of Figure 7 we plot the main diagnostic plot to be used throughout the remainder of this paper, PC1 vs. PC2. This is our new equivalent of $\text{D}_n(4000)$ vs. $\text{H}\delta_{\text{A}}$, although should be thought of as 4000Å break strength vs. *excess* Balmer line strength, i.e. the inverse-correlation between $\text{D}_n(4000)$ and $\text{H}\delta_{\text{A}}$ has already been accounted for in PC1. In the top-right panel of Figure 7 we plot PC1 vs. PC3, the index which measures excess Ca II absorption. For comparison with previous work, the bottom-left-hand plot in Figure 7 shows $\text{D}_n(4000)$ vs. $\text{H}\delta_{\text{A}}$ for a high SNR subsample of the galaxies. In all panels our SDSS galaxy-bulge sample is plotted in greyscale; in regions of low number density, individual galaxies are plotted as points. The quiescent cloud (red sequence) with large 4000Å break strength is clear in all plots, the star forming sequence extends to lower values of PC1. The tail to the bottom left of PC1/2, with small 4000Å break and very weak Balmer lines, is composed of galaxy bulges with stellar populations dominated by O or B star spectra, i.e. experiencing a starburst. The ‘hump’ in PC1/2 over the starforming sequence are stellar populations with stronger than average Balmer absorption lines, i.e. candidates for populations which experienced a strong burst of star formation in the past.

The overplotted tracks follow the evolution of a 0.03 Gyr tophat model starburst, superimposed on a composite quiescent galaxy, created from galaxies in our quiescent class (Section 7.1). This approach isolates the small discrepancies between the model and SDSS spectra for old populations (see Section 6.1). The burst strength is characterised by the mass of stars formed during the burst, compared to the mean mass of the galaxies within the composite spectrum; we plot four burst tracks of strengths 0.5%, 1%, 3% and 20%. The stars indicate times after the onset of the burst of 0.0001, 0.01, 0.2, 0.5, 1.0 and 1.5 Gyr.

Looking at the starburst tracks in PC1/2, we can see the familiar degeneracy between the age and the strength of the burst. The ‘post-starburst’ objects in the ‘hump’ could be galaxies that have undergone a massive starburst a relatively long time ago, or a

smaller starburst more recently. This degeneracy is also present in $\text{D}_n(4000)$ vs. $\text{H}\delta_{\text{A}}$. PC3 allows the degeneracy to be broken however, by making use of the rapidly changing Ca II line strength between A and F stars.

As discussed in Section 1, it remains unclear as to whether galaxies with strong Balmer absorption lines have indeed experienced a recent burst of star formation in the past (post-starburst), or whether the star formation has simply been shut-off (truncation), for example by interaction between the intracluster medium and the galaxy’s interstellar medium as it enters a cluster environment or by feedback associated with the rapid growth of a black hole. For a single galaxy, distinguishing these scenarios from our stellar continuum measures alone is difficult; shutting off the star formation in the continuous star formation histories, causes galaxies to move upwards in PC2. However, taking the population of galaxy-bulges as a whole provides additional constraints. In particular, the truncation model does not explain the relatively large number of bulges that are undergoing starbursts, while these are the natural progenitors of the post starbursts in our sample. We invoke Occam’s Razor and will not discuss such truncation models further in this paper.

6 POTENTIAL BIASES AND COMPLICATIONS

In Figure 8 we investigate the effect of several potential systematic effects on the starburst evolution tracks: a change in stellar library, dust, changing the underlying old population, burst metallicity and an overall change in velocity dispersion.

Stellar libraries: Figure 8a compares the results using two different observational stellar libraries input into the GALAXEV code of BC03, Stelib (Le Borgne et al. 2003) and MILES (Sánchez-Blázquez et al. 2006). Note that the implementation of the MILES library in the GALAXEV code is preliminary. Very little difference is observed except for a small offset in the hottest stars.

Dust: Figure 8b shows the effects of dust in the burst stellar population. The dust prescription implemented is the two phase model of Charlot & Fall (2000) in which stars older than 10^7 years are extinguished at a level of 30% that of the young stars. We compare dust free models with dusty model galaxies in which young stars suffer one magnitude of attenuation in the V-band ($A_V = 1$). The presence of dust causes an apparent small reduction in burst strength.

Underlying old population: The biggest effect on PC3 is caused by a change in mass of the underlying old stellar population. As young stellar populations have only weak Ca II lines, the old stellar population greatly affects their total strength. In Figure 8c a high and low stellar mass composite has been created [$\log(M_*/M_\odot) < 10.25$ or > 11.0]. The increase in PC3 with stellar mass may be due to several effects: the high mass galaxies have higher velocity dispersions (see e), higher metallicities and are more likely to be α -enhanced.

Metallicity: Figure 8d compares starburst tracks of two different metallicities, $Z = 0.4 Z_\odot$ and $Z = 2.5 Z_\odot$. The same quiescent composite has been used. In PC1/2 the lower metallicity causes an apparent reduction in burst strength. In PC3 we see again that Ca II is affected by metallicity, but the effect only becomes visible in intermediate age populations where Ca II is stronger.

Velocity Dispersion: Figure 8e compares models with velocity dispersions of 112 and 225 km s^{-1} . Recall that the eigenspectra are created with velocity dispersions of 150 km s^{-1} . To isolate the velocity dispersion effect, the same low stellar mass quiescent

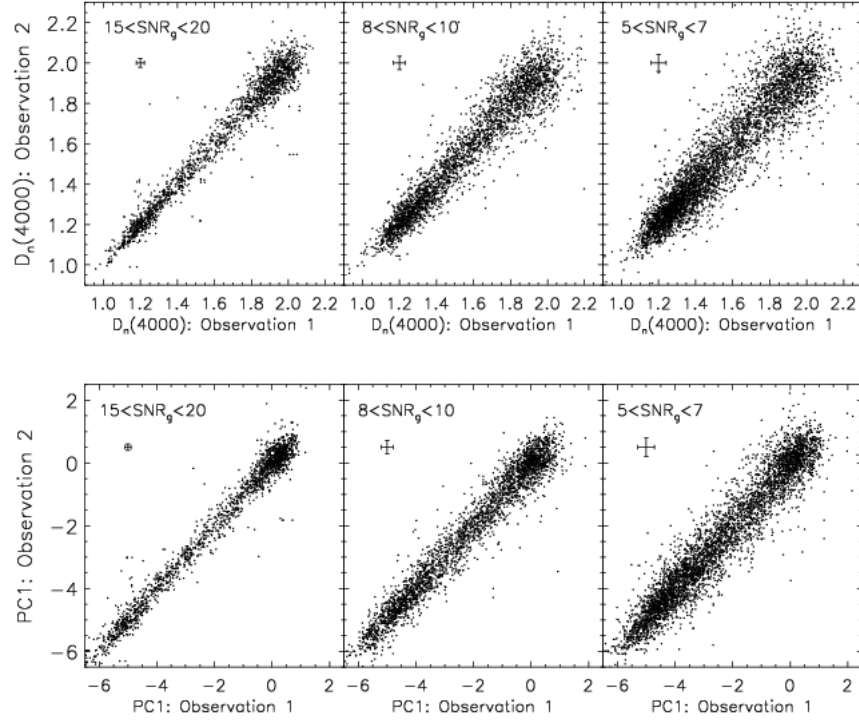


Figure 5. Comparison of the scatter between measurements of $D_n(4000)$ (top) and PC1 (bottom) in SDSS galaxies which have been observed twice. The sample is split according to per pixel SNR in the g -band as indicated in the top left. Median 1σ statistical errors on the quantities for each sample are indicated in the upper left.

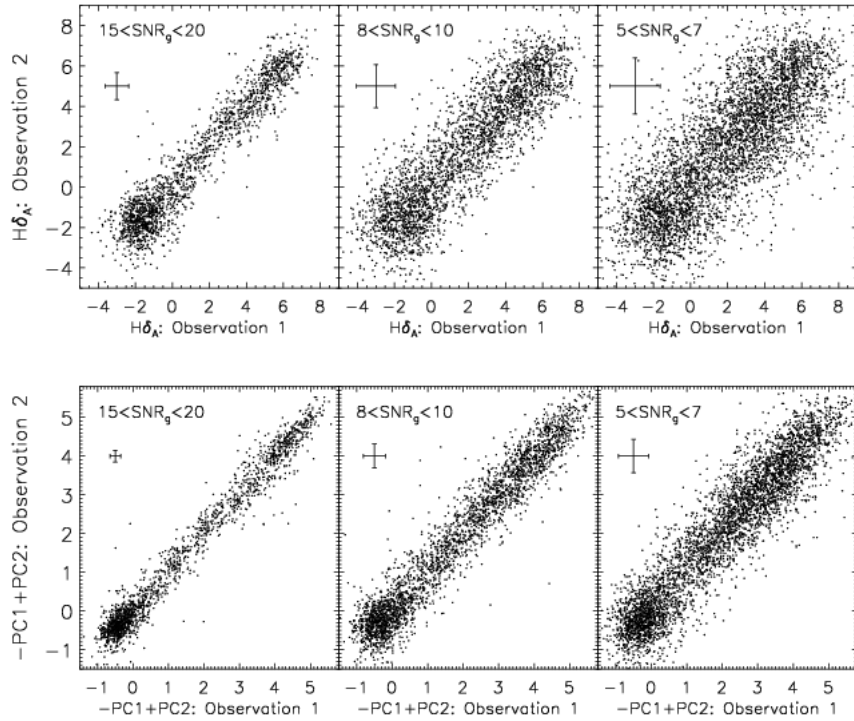


Figure 6. Comparison of the scatter between two measurements of $H\delta_A$ (top) and $-PC1+PC2$ (bottom) in SDSS galaxies which have been observed twice. The sample is split according to per pixel SNR in the g -band as indicated in the top left. Median 1σ statistical errors on the quantities for each sample are indicated in the upper left.

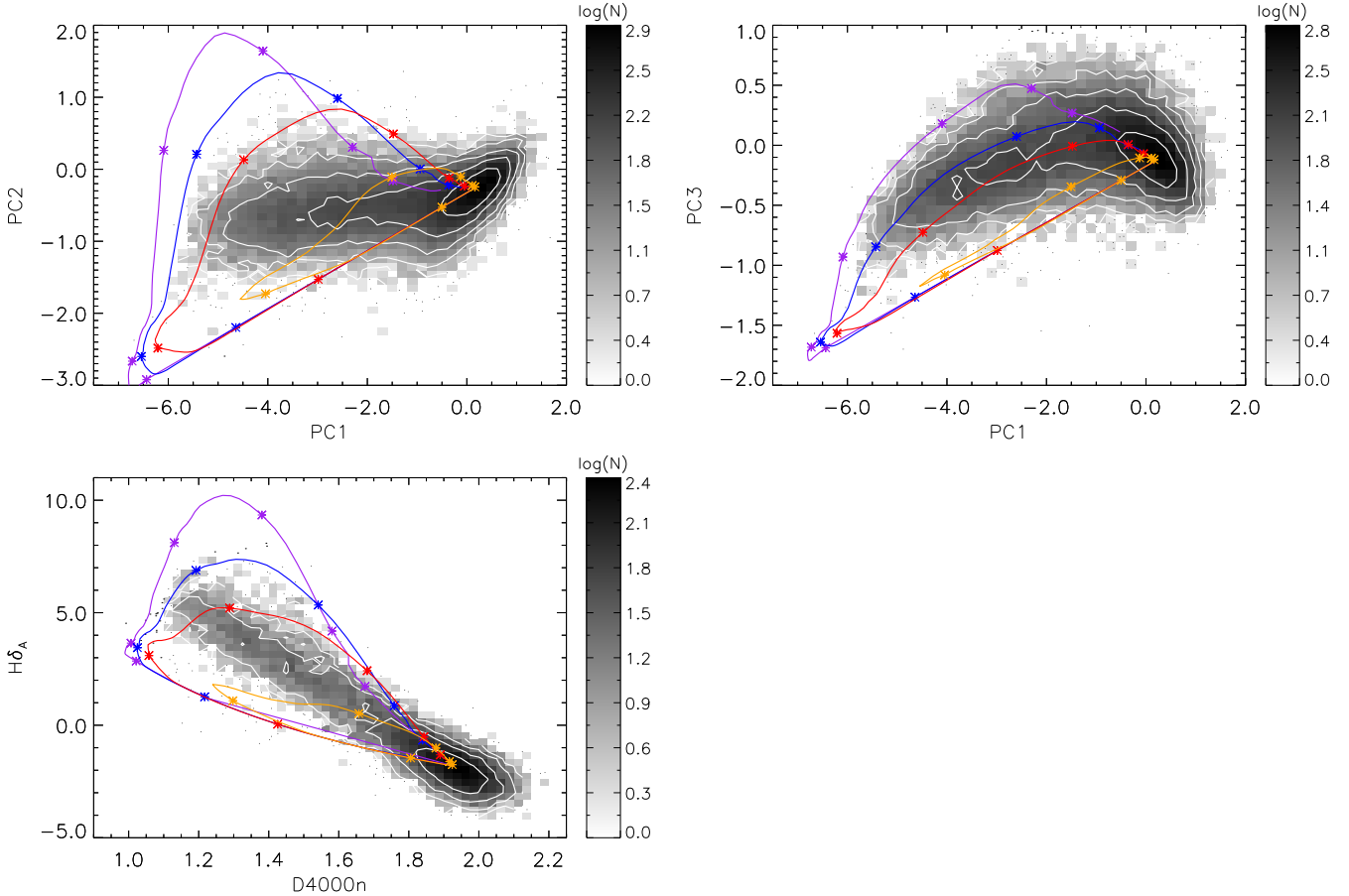


Figure 7. In greyscale: the joint distributions of PC1 vs. PC2 (top left) and PC1 vs. PC3 (top right) and $D_n(4000)$ vs. $H\delta_A$ for the spectra of high stellar surface mass density, low- z SDSS galaxies. The greyscale indicates logarithmic number of objects. In regions of low number density, individual points are plotted in black. The galaxies in the $D_n(4000)/H\delta_A$ plot are additionally constrained to have g -band SNR/pixel greater than 20. PC1 is equivalent to $D_n(4000)$, PC2 measures excess Balmer line strength and PC3 measures excess Ca II line strength. Overplotted as tracks are model Bruzual & Charlot (2003) tophat starbursts of 0.03 Gyr duration, superimposed on a composite early type galaxy spectrum. Asterisks indicate times after the initial starburst of 0.001, 0.01, 0.1, 0.5, 1.0 and 1.5 Gyr. With a mean stellar mass of $4.3 \times 10^{10} M_\odot$ for the early type galaxies in the composite, burst mass fractions are 0.5% (orange), 1% (red) and 3% (blue) and 20% (purple).

population has been used for both, and convolved up to the higher velocity dispersion for the dotted tracks. A small effect is seen on all components.

6.1 Offset in indices between models and data

We note that there is an offset between the exponential star formation history BC03 model galaxies and the SDSS data in $D_n(4000)$ vs. $H\delta_A$, where none was previously apparent (see Figure 3 in Kauffmann et al. 2003b). This mismatch results from spectrophotometric calibration differences between the SDSS dataset and stars in the Stelib stellar spectral library (Le Borgne et al. 2003), which underpins the BC03 models. The difference between earlier work and the current analysis is primarily in the spectrophotometric calibration of the SDSS spectra between DR1 and DR2 (Abazajian et al., 2004). A new version of models is under construction using the new MILES stellar library (Sánchez-Blázquez et al. 2006), which solves this problem (G. Bruzual, private communication). The magnitude of the effect is ~ 0.1 mag in $D_n(4000)$ and 1\AA in $H\delta_A$ (see also the comparison in Sánchez-Blázquez et al. 2006).

The effect on the principal component amplitudes of a mismatch in 4000\AA break strength between models and data is not

immediately intuitive. PC2 is in fact worst affected, because the primary variance in the data is the shape of the continuum and it is this that PCA concentrates on fitting first. Because of the anti-correlation between 4000\AA break and Balmer line strength, the best fitting first component then has too strong Balmer lines and PC2 must be used to counterbalance some of this. An additional effect, visible in the reconstructions of some starforming spectra, is a subsequent mismatch in the far blue continuum shape. An offset in PC3 is expected, due to the incorrect amount of Ca II being introduced by the other two components.

We expect the current problem with the spectral synthesis models to be solved in the very near future, however, it is clear that systematic errors on derived parameters from spectral synthesis models may be significantly larger than the statistical errors usually quoted. In this paper we are unaffected by such problems, as we do not attempt to derive full quantitative solutions of burst parameters for our galaxies. In future papers it will be important to consider comparison between different spectral synthesis models, such as those based on synthetic stellar libraries (González Delgado et al. 2005).

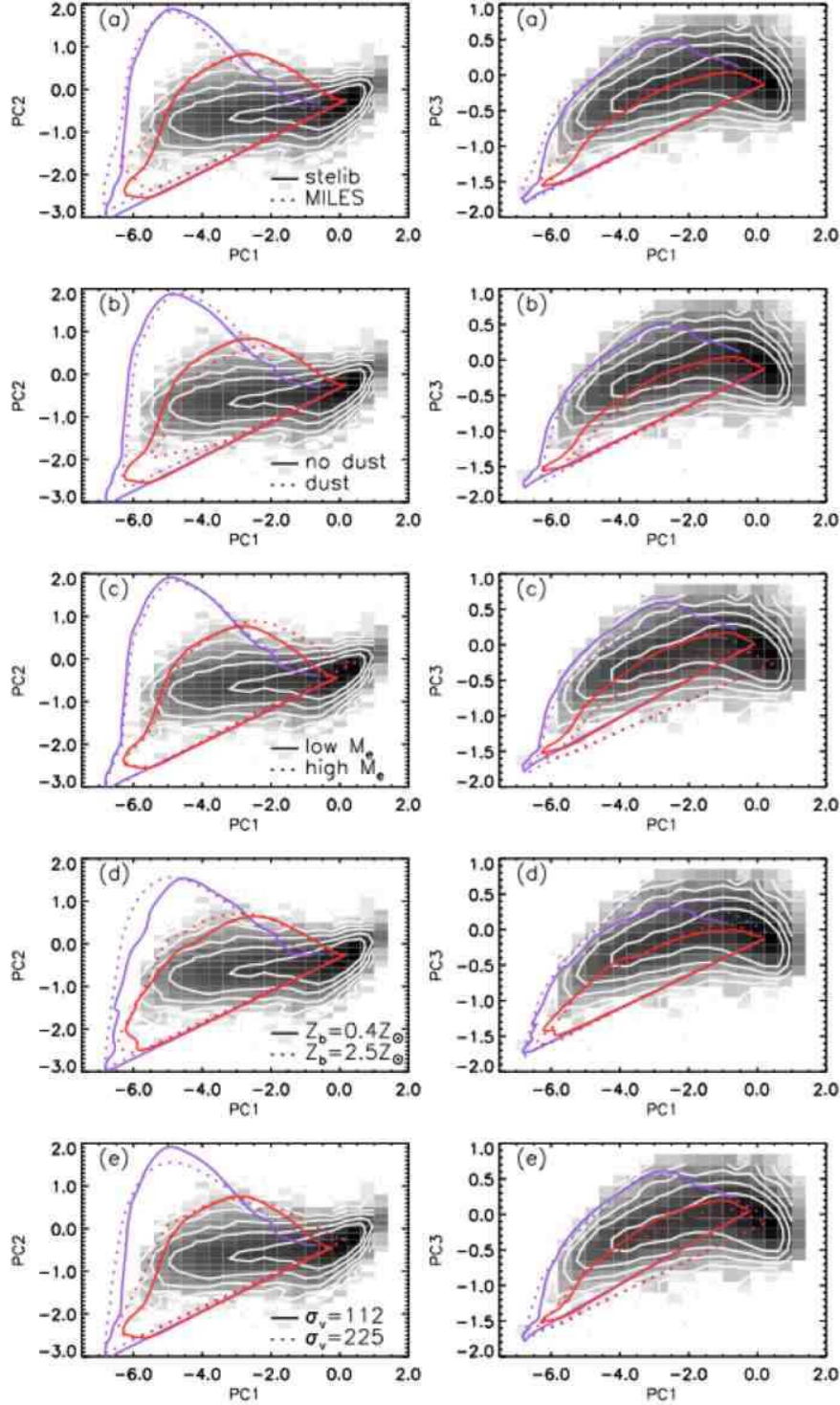


Figure 8. In greyscale: SDSS galaxies. Overplotted starburst tracks are for tophat bursts with mass fractions of 1% and 3% as in Figure 7. For each burst strength two sets of starburst tracks are plotted as continuous or dotted lines: a) based on the Stelib or MILES stellar libraries; b) with or without dust; c) with metallicities of 0.4 or 2.5 solar; d) with a low or high stellar mass early type composite; (e) with velocity dispersions of 112 or 225 km s⁻¹.

6.2 Emission line infilling

One of the most difficult parts of fitting models to the stellar component of a galaxy spectrum is the contamination of the data spectrum by non-stellar light. Nebular emission lines are one such contam-

inant that we must be particularly cautious of, as they affect the Balmer absorption lines in which we are particularly interested.

We selected a subsample of objects with H δ emission and compared the three principal component amplitudes obtained with and without masking the centers of the H δ through H10 absorption

lines. A clear emission line equivalent width limit was found below which the amplitudes remained unbiased. Above this limit (given in Section 4) we mask the centers of the absorption lines before calculating the amplitudes. Additionally, the flux normalisation of the spectra is crucial, as the emission lines sit preferentially in the centers of absorption lines, it is thus preferable to leave normalisation as a free parameter when calculating the component amplitudes (Section 4).

We note that for strongly star-forming systems, the second principal component primarily fits the overall shape of the continuum i.e. the strong blue emission from the hot stars, rather than the strength of the Balmer absorption features.

6.3 Contamination by AGN continuum light

There is a population of objects which scatter below the star-forming branch of the PC1/2 plane, with weak Balmer absorption lines for their 4000Å break strength. Further investigation of these spectra show them to be objects with apparently old stellar populations, but some excess blue continua. A proportion of these are weak Type 1 AGN in which some broad line component is visible in the stronger Balmer emission lines. Many others are found to have radio (FIRST) and/or soft X-ray (RASS) counterparts, and are most likely weak BL Lacs (e.g. Collinge et al. 2005). To the PCA analysis the featureless blue AGN continuum looks very similar to the blue continuum of young O and B stars, weakening the Balmer series and 4000Å break in a similar way (see also Hao et al. 2005). A stellar population study of these objects from their optical spectra alone is beyond the scope of this initial paper, and we simply treat them as a separate class of objects. Dust- or electron-scattered continuum light from the hidden AGN in Type 2 AGN (the AGN type that dominates our sample) has been shown contribute negligibly to the blue continuum light in all but the most extreme AGN (Schmitt et al. 1999; Kauffmann et al. 2003a; Zakamska et al. 2006).

7 RESULTS: THE RECENT SFH OF LOCAL GALAXY BULGES

We now turn to the application of our method presented in Sections 3 and 4, to the SDSS dataset presented in Section 2. We focus on the AGN properties as a function of recent star formation history in the bulge, and in particular on the properties of the bulges with excess Balmer absorption which have undergone a more unusual recent star formation history.

The tight correlation observed between supermassive black hole mass and velocity dispersion in galactic bulges (Ferrarese & Merritt 2000; Gebhardt et al. 2000) is well explained by theoretical models in which black hole and spheroid growth are linked (e.g. Haehnelt & Kauffmann 2000; Adams et al. 2001; Granato et al. 2004). Observationally there is much evidence for the coincidence of recent or ongoing star formation activity with AGN activity in Seyfert 2s (Heckman et al. 1997; González Delgado & Heckman 1999; Schmitt et al. 1999; González Delgado et al. 2001; Raimann et al. 2003; Cid Fernandes et al. 2004), type 2 QSOs (Zakamska et al. 2006), LINERS (Cid Fernandes et al. 2005) and powerful FR II radio galaxies (Tadhunter et al. 2005). This strongly suggests a positive link between the accretion of matter onto the black hole and an increase in bulge size through starbursts. However, the relationship is clearly complicated, with the fraction of objects identified with

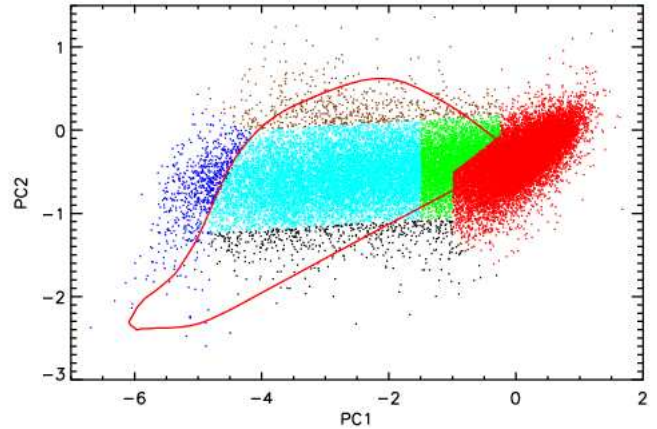


Figure 9. Defining classes of stellar population for galaxy bulges. The joint distribution of PC1 vs. PC2 with galaxy bulges classified as quiescent (red), green-valley (green), star-forming (cyan), starburst (blue) and post-starburst (brown) and other (black) according to their position in the PC1/2 plane. We caution that there are no distinct breaks in the distribution, and each class is a continuation of the others. To guide the eye in comparison with subsequent figures, a single weak instantaneous burst track of 1% burst fraction is overlotted.

young stellar populations apparently varying with AGN type and strength. Uncovering the stellar populations of Type I AGN hosts remains very technically challenging, with limited agreement between different studies (Canalizo & Stockton 2000; Nolan et al. 2001; Canalizo et al. 2006; Yip et al. 2004).

The majority of present day black hole growth is found to occur during relatively high accretion rate phases on to low mass black holes (Heckman et al. 2004). We may expect to find that recent star formation correlates with accretion rate, with newly available gas reservoirs at the center of the galaxy either concurrently forming stars and feeding the black hole, or forming stars which subsequently fuel the black hole. Large homogeneous samples are required for such an analysis, such as those available with spectroscopic studies such as the SDSS. In these studies, less detailed data is compensated for by being able to study the average properties of hundreds of thousands of objects. Kauffmann et al. (2003a) detect significant trends with AGN strength in the stellar populations of galaxies hosting obscured AGN, finding that AGN with higher [O III] luminosity are contained in hosts with younger mean stellar ages and with a higher likelihood to have undergone a recent starburst. In this section we follow on from this work using our new, higher SNR stellar population indicators to quantify more precisely the recent star formation of central galaxy bulges with and without the presence of an AGN. We investigate trends with [O III] luminosity, dust content and irregularity of morphology.

7.1 Stellar population classes

Our sample of galaxies is described in detail in Section 2. In Figure 9 we have split the sample into six different classes according to their position in the PC1/2 plane: quiescent, “green-valley”, star-forming, starburst and post-starburst⁵. Except for the post-starburst

⁵ The sixth class contains objects that appear to be contaminated by scattered AGN light (see Section 6.3). As the line parameters derived from

Table 1. The number of objects in each class, classified by narrow emission line ratios as AGN/composite, star-forming or unclassifiable (due to non-existent or weak emission lines). The values in brackets are after correcting the numbers for survey volume effects using the $1/V_{\max}$ method (Section 2). The final column gives the mean of the logarithmic specific star formation rate (SSFR) derived by Brinchmann et al. (2004) for each class.

Class	AGN+comp	SF	unclass	Total	$\langle \log(\text{SSFR}) \rangle$
Quiescent	5226 (6128.)	54 (63.)	13178 (15330.)	18458 (21523.)	-11.77
Green Valley	2297 (2601.)	180 (209.)	953 (1088.)	3430 (3900.)	-11.15
Star forming	3611 (4090.)	5056 (5729.)	1027 (1191.)	9694 (11010.)	-10.26
Starburst	58 (66.)	694 (770.)	6 (7.)	758 (844.)	-9.68
Post-starburst	364 (415.)	178 (215.)	92 (104.)	634 (735.)	-10.41
Other	195 (233.)	195 (235.)	150 (190.)	540 (659.)	-10.67
total	11751 (13537.)	6357 (7222.)	15406 (17913.)	33514 (38673.)	-11.19

and quiescent populations, the exact positioning of the class divisions is fairly arbitrary as there are no well defined minima, as seen, for example, in the bimodality of the galaxy population as a whole. Table 1 presents the numbers of galaxies within each class, split according to their emission line ratios as AGN or star-formation dominated. To give some physical meaning to each class, the final column gives the mean logarithmic specific star formation rate of each class, as derived by Brinchmann et al. (2004), see e.g Fig. 25 of that paper for a comparison with all star-forming galaxies. We note that for AGN, these values are derived from $D_n(4000)$ rather than the emission lines. Figure 10 presents composite spectra of all galaxies in each class. Note the strong emission lines present in the post-starburst class: selection of such objects based on the lack of [O II] or $H\alpha$ emission lines will select only a very small subsample of those galaxies found to have excess A star populations in this paper. We will return to this point in Section 8.3. Brinchmann et al. (2004) showed that $D_n(4000)$ correlates well with specific SFR within the fibre aperture derived from emission line strengths, and Figure 4 shows that PC1 is equivalent to $D_n(4000)$, therefore, except for the post-starburst population, our different classes simply describe a sequence in specific SFR.

In our simple instantaneous burst model, the galaxy bulge leaves the quiescent (red sequence) or green-valley populations as soon as a central starburst occurs and, if the starburst is strong enough, almost instantaneously appears in the bottom left of the diagram. This stellar population ages, without new stars being formed, and moves along a track similar to the ones indicated in Figure 7 with the precise track depending primarily on the fraction of stars formed in the burst. Before a starburst of more than $\sim 1\%$ mass fraction returns into the green valley, or red sequence, it passes through the “post-starburst” phase where excess Balmer absorption is evident. Within this model, some of the bulges classified as “star-forming” may simply be undergoing smaller, or more extended bursts of star formation and are not necessarily equivalent to the star-forming branch of the general galaxy population which are believed to have experienced almost constant star formation for most of their lives.

In the following subsections we will look in detail at the morphological, dust and AGN properties of each of these classes. As discussed in Section 2, because our sample is magnitude limited, throughout the paper we weight each galaxy contributing to a mean or total quantity by the inverse of the maximum volume in which it may be observed in the survey. This correction is in-

cluded in all our figures where appropriate. In the following subsections, 2-dimensional histograms weighted by physical properties were created using an adapted version of the adaptive mesh algorithm of Cappellari & Copin (2003), in order to avoid bins containing a small number of objects biasing our perception of overall trends. Bin boundaries are set such that each bin has roughly constant signal-to-noise ratio equal to the square root of the number of galaxies contributing to that bin.

7.2 Morphology

The merger of, or interaction between, two galaxies is known to induce starbursts and recent major mergers are often suggested to be the cause of galaxies with strong global post-starburst stellar populations (e.g. Liu & Kennicutt 1995). Numerical simulations of gas rich mergers also produce starbursts (Di Matteo et al. 2005; Cattaneo et al. 2005) and indicate that dynamical signatures on the merger remnants can remain for as much as several Gyr after the original merger (Cox et al. 2006). Even minor mergers may cause the triggering of nuclear starbursts, as small disruptions to the gravitational potential of a galaxy allow gas to lose angular momentum and flow towards the center (e.g. Mihos & Hernquist 1994). In this section we investigate trends of global galaxy morphology (from SDSS photometry) with the stellar populations in the central galaxy bulges.

To give a visual impression of the type of galaxies that host bulges residing in the different regions of the PC1/PC2 diagram, Figures B1 to B5 show montages of 1 arcmin square SDSS postage stamp images of samples of objects from each main region: the quiescent, green-valley (younger mean stellar age than the quiescent), star-forming sequence, starbursts (spectra dominated by O and B stars), post-starbursts (stronger Balmer absorption lines). In the top left of each montage, the size of an SDSS fibre is indicated: our spectral analysis relates only to the central population of stars. Only objects with $z < 0.05$ have been selected for these montages, where details such as disturbed morphology and disks are more readily visible.

A few obvious trends are worth noting. Figure B1: Bulges with quiescent stellar populations are in general hosted by elliptical and S0 galaxies. Figure B2: Galaxies with bulges which lie in the “green-valley” show a greater preponderance of outer disk structures and irregular morphologies than those with quiescent populations. Figure B3: A few disturbed morphologies are also apparent in hosts with star-forming bulges and the galaxies are more likely to have disks, particularly as their specific SFR increases (PC1 decreases). Figure B4: About half of the galaxies with bulge stellar

model fits to these spectra are unlikely to be robust, we do not discuss this class further here.

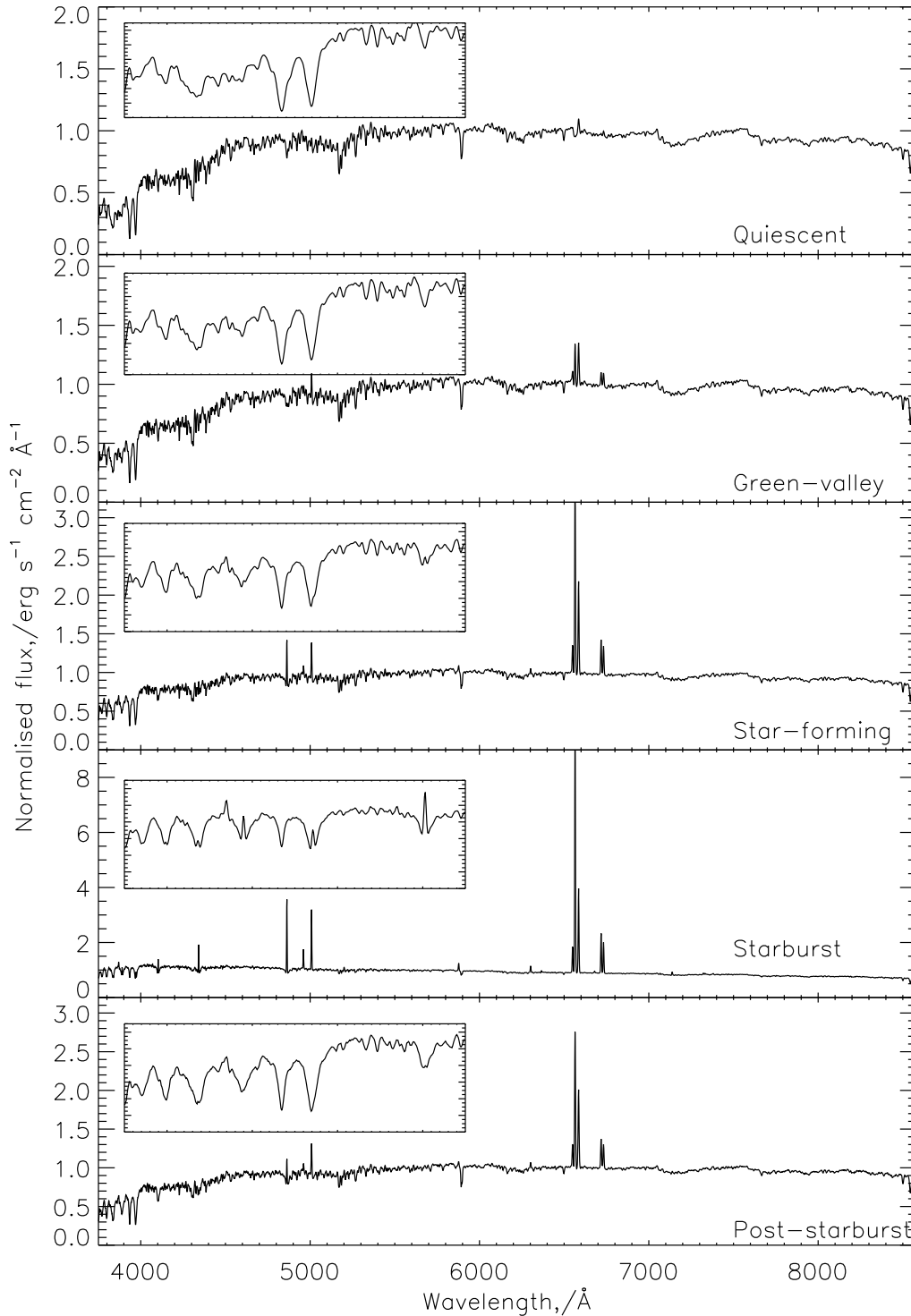


Figure 10. Composite spectra of galaxy-bulges within each PCA-defined “class”. The inset shows the composite in the wavelength region used during our analysis of the recent SFH of the galaxies, normalised to the same flux scale for each class.

populations that are dominated by very young O and B stars (strong starbursts) are globally morphologically disturbed, however, it is clearly not a necessary requirement and few Toomre & Toomre (1972) mergers are found in our high stellar surface mass density sample. Finally, in Figure B5, bulges with excess Balmer absorption lines reside in on average slightly more compact systems, how-

ever evidence of recent dynamical disturbance, such as dust lanes, tidal tails or close companions are visible in more than half. We will return to the last Figure in the series in Section 8.3.

A quantitative analysis of the global structure of the galaxies is possible via the “concentration index” which distinguishes ellipticals from spirals based on their radially averaged light dis-

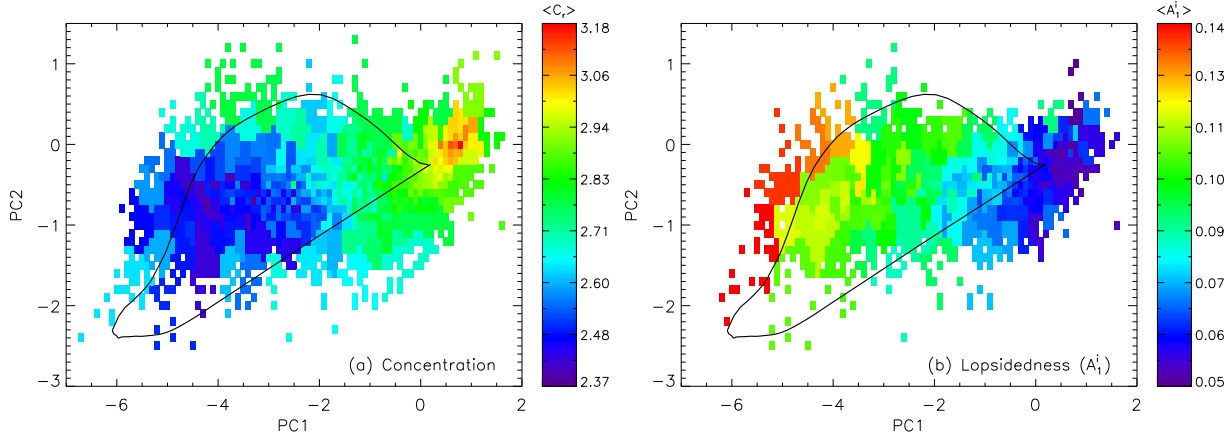


Figure 11. Galaxy morphology as a function of stellar population of the bulge. Each 2D histogram bin has been weighted by the mean volume-weighted concentration index (*left*) or mean volume-weighted lopsidedness (*right*) of the galaxies within that bin. Concentration index is defined to be the ratio of Petrosian radii R_{90}/R_{50} in the r -band; elliptical galaxies in general have $C > 2.6$. Lopsidedness quantifies any large scale overabundance of light on one side and corresponding underabundance on the opposite side of the galaxy and is measured in the i -band (Reichard et al. 2007). It thus provides information additional to the radially averaged concentration index and is sensitive to morphological disturbance. Note that fewer galaxies have measured lopsidedness values than concentration indices (see text). A single weak instantaneous burst track of 1% burst fraction is overplotted.

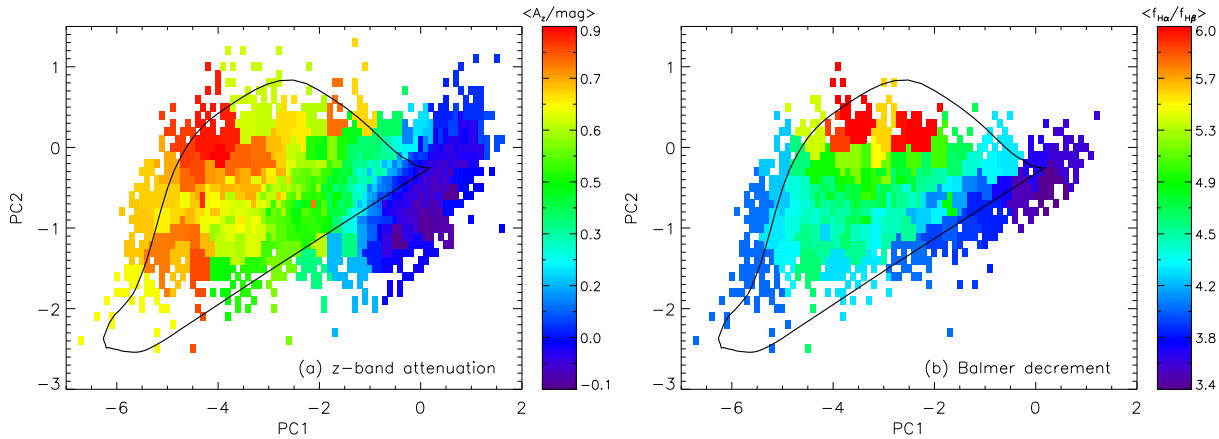


Figure 12. *Left:* The volume-weighted mean z -band dust attenuation of galaxies in each joint PC1/2 histogram bin (A_z from Kauffmann et al. 2003b). *Right:* The volume-weighted mean Balmer decrement of galaxies in each bin, defined as $f_{H\alpha}/(f_{H\beta})$ where $f_{H\alpha}$ ($f_{H\beta}$) is the emission flux of $H\alpha$ ($H\beta$) corrected for underlying stellar absorption (Brinchmann et al. 2004). Note that fewer galaxies have measured Balmer decrements than A_z measurements, because the former require significant emission line fluxes. A single weak instantaneous burst track of 1% burst fraction is overplotted.

tributions. We define the concentration index to be the ratio of the radii containing 90% and 50% of the Petrosian flux in the r -band ($C_r = R_{90}/R_{50}$). This parameter has been shown to be correlated with galaxy morphology (Strateva et al. 2001): elliptical galaxies have values around 3 and disk-dominated galaxies have values around 2 to 2.5. The classes are often divided at 2.6. In Figure 11a we weight each joint PC1/PC2 histogram bin by the mean concentration of galaxies contained within that bin. There are two noticeable trends. Firstly, as suggested by the image montages, the galaxies hosting bulges with progressively larger specific star formation rates (more negative PC1) have lower mean C_r i.e. more exponential profiles. Secondly, the post-starburst bulges exist in, on average, more centrally concentrated (higher C_r) galaxies than galaxies with similar mean stellar ages. Finally, it is noticeable that the strongest starburst bulges to the far right of the figure are found to have slightly higher concentrations than the galaxies with more ordinary recent star formation histories and less negative PC1. This

is evidence in favour of our suggested toy model, i.e. that the starburst class is formed by otherwise quiescent bulges experiencing bursts of star formation, rather than being a more extreme class of the ordinary star forming branch of galaxies.

A statistical measure of galaxy ‘lopsidedness’ (Reichard et al. 2007), allows us to investigate the second order distribution of light in a galaxy, beyond the radially averaged concentration index. A galaxy’s lopsidedness is quantified through a fourier decomposition of its light, such that the first component quantifies any large scale overabundance of light on one side and corresponding underabundance on the opposite side of the galaxy. Lopsidedness has only been reliably measured for galaxies with $z < 0.06$ or Petrosian r -band magnitude < 16.8 ; very inclined galaxies, with $b/a < 0.4$, are also excluded. Our sample contains 16722 galaxies. The lopsidedness values used in this paper are derived from the i -band light, which best represents the older stellar population and therefore true perturbations in the gravitational potential of the galaxy rather than

uneven ongoing star formation. In Figure 11b we weight each joint PC1/PC2 histogram bin by the mean *i*-band lopsidedness of galaxies contained within that bin. We see the same trend of increasing lopsidedness with decreasing mean stellar age as observed in $D_n(4000)/H\delta_A$ by Reichard et al. We also see that the most lopsided galaxies are those that lie along the left edge of our distribution i.e. galaxies hosting bulges with the strongest ongoing star formation through into the post-starburst bulge class. Excess lopsidedness exists right into the post-starburst bulge class, where their concentration indexes have already shown that they are becoming more elliptical. However, it is clear that these are a mixed population in terms of lopsidedness and investigation of objects on a more individual basis is warranted.

The image montages alone present a strong case for a physical link between the recent SFH of the bulge and global galaxy structure, although any relationship is clearly far from one-to-one. The trends we find of galaxy concentration and lopsidedness with recent SFH of the bulge strongly suggest that *at least some of the central starbursts and post-starbursts are caused by mergers, with galaxies becoming more centrally concentrated after the merger, but with excess lopsidedness existing up to a Gyr after the starburst has occurred in the bulge.*

7.3 Dust

The presence of dust (cold gas) is intimately connected with star formation. In mergers large quantities of gas can be concentrated near the nucleus and the resulting high dust column densities lead to very large attenuations: extreme examples are the Ultra Luminous Infra Red Galaxies (ULIRGS). Dust is also produced in significant quantities by Asymptotic Giant Branch (AGB) stars, which first appear around 10^8 years after a starburst. This is similar to the probable ages for our post-starbursts. It has been known for many years that dust is also present in many galaxies that are morphologically classified as early-type, in contradiction to the standard view of the Hubble sequence (Sadler & Gerhard 1985). The presence of dust and an AGN may also be closely linked (Kauffmann et al. 2006; Lopes et al. 2007, and references therein).

In Figure 12a each histogram bin is weighted by mean dust content of galaxies in that bin, as measured by the attenuation in the *z*-band (A_z) derived from the colour of the stellar continuum by Kauffmann et al. (2003b). In Figure 12b the bins are weighted by the observed $H\alpha$ to $H\beta$ emission line flux ratio (Balmer decrement), after correcting for underlying stellar absorption (Brinchmann et al. 2004). Only those galaxies with $H\alpha$ and $H\beta$ flux measured at greater than 3σ confidence and flux in the $H\beta$ line is greater than $4 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$ are included in the latter figure. To first order A_z can be thought of as attenuation of light from the older stellar population, and the Balmer decrement measures the dust attenuation suffered by light from the younger stellar population. In general they are well correlated in the SDSS galaxies, albeit with significant scatter, suggesting that star forming regions and older stellar populations are on average well mixed.

The expected overall trend of increasing dust content with increasing specific SFR is seen in both panels of the figure. However, two very interesting trends are seen along the strong starburst track, particularly in panel b. Firstly, the starburst galaxies are *less* dusty on average than galaxies at slightly lower PC1 (lower specific SFR). Secondly, a sharp *increase* in dust content is observed in the strong Balmer absorption line objects. Qualitatively, this trend fits with our toy model, in which the objects along the strong starburst track have experienced a recent sharp increase in their star

formation rates and evolve into the post-starburst objects. Our plots suggest that this occurs as the first generation of stars from the starburst begin to produce dust. While the spread in observed Balmer decrements in this class is large, *the post-starburst bulges appear to have on average considerably more dust surrounding the line emitting sources, compared to diffuse interstellar dust, than seen in any other class of galaxy bulges.* We will return to this point in more detail in the discussion.

7.4 The stellar populations of AGN host bulges

One of the key aims of this project was to quantify the very recent star formation history of bulge stellar populations without relying on nebular emission lines which, in a large fraction of our sample, are contaminated by AGN emission. In this subsection we exploit our success by examining the stellar populations in the bulges hosting the AGN. We use the attenuation-corrected [O III] luminosity as an indicator of AGN luminosity because [O III] is generally the strongest optical emission line of Type 2 AGN, and suffers significantly less than the other strong lines from contamination by emission excited by star formation. Heckman et al. (2004) find that $>90\%$ of [O III] luminosity arises from the AGN when objects lie above the theoretical Kewley et al. (2001) demarcation line on the BPT diagram, although this can drop to as low as 50% as objects approach the empirically determined, less stringent division of Kauffmann et al. (2003a).

We first ask the question: where do the bulges that host AGN live in PC1/2 space? In Figure 13 we show the joint number count distributions in PC1 and PC2 for our dataset split into four samples according to their narrow emission line ratios: pure-AGN, AGN including composite objects, pure-star-forming and unclassified (see Section 2.1). As with all figures and quoted numbers, galaxies are weighted by $1/V_{\text{max}}$ so that these figures reflect the true comoving number density of each class. Galaxies which lie in the lowest density regions of the plots are included as individual points to indicate the distribution of outliers. As usual, to guide the eye in comparison between different panels, a single, weak instantaneous burst track is overplotted with a burst fraction of 1% (see caption to Figure 7).

Figure 13a shows that the host galaxies of “pure” AGN have predominantly quiescent stellar populations, although some are found in star-forming galaxies and a large fraction of post-starbursts fall into this category. If the composites are included, however, AGN span a much wider range in star formation history (Figure 13b). AGN are less likely to be found in bulges with very young mean stellar ages (Figure 13c); it is likely, however, that some strongly star-forming galaxies do contain AGN, but the emission lines from the narrow-line region are weaker than those produced by the H II regions in the galaxy, and are thus not detectable. As expected, the unclassified objects (Figure 13d) lie predominantly in the quiescent cloud, i.e. they have little ongoing star formation. Some unclassified objects are also found extending into the star-forming and post-starburst region; as we will show in section 7.4.2, particularly in the case of the post-starburst bulges this is caused by strong dust obscuration of the shorter-wavelength emission lines.

7.4.1 Contribution to AGN luminosity and black hole growth rate

The AGN in our sample span a broad range in power (broad range in [O III] luminosity), so Figure 13 paints a potentially misleading picture of the link between the star formation history of bulges and

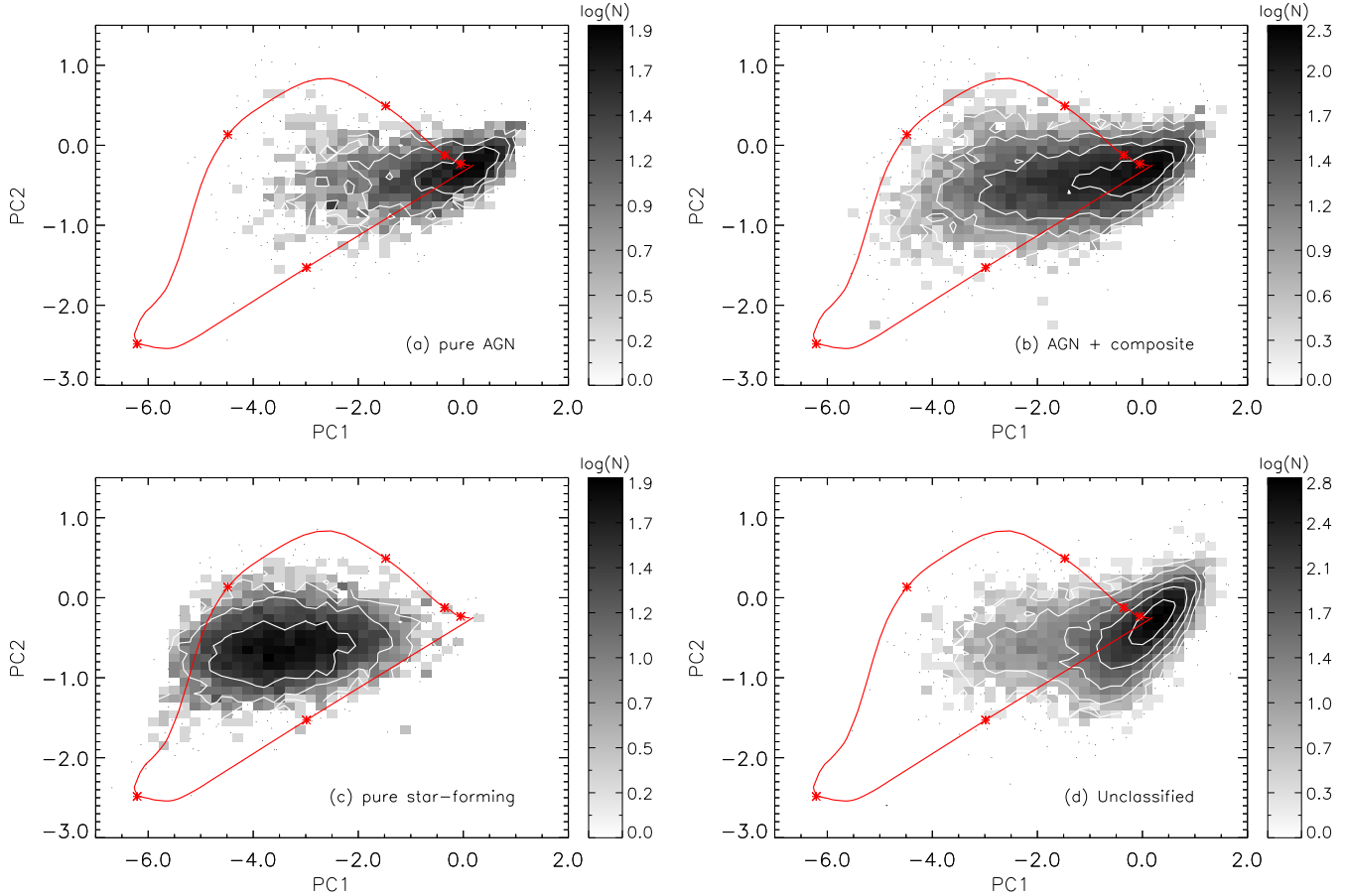


Figure 13. Joint number distribution (volume-weighted) of PC1 and PC2 for SDSS galaxies classified as pure AGN, AGN (including composite objects), pure star-forming, or unclassified. In regions of low number density, individual points are plotted. Objects are classified according to their narrow emission line flux ratios $[N II]/H\alpha$ and $[O III]/H\beta$. Unclassified objects are those without all emission lines above the requisite SNR. As can be seen, this is in general because their stellar populations are old. A single weak instantaneous burst track of 1% burst fraction is overlaid.

the growth of black holes. Thus, in Figure 14 we use the $[O III]$ luminosity of AGN to illustrate the distribution of the growth of black holes as a function of the star formation history of their host bulge. In this figure, we include all AGN and composite objects, but exclude objects with lines dominated by star formation and objects for which an accurate ($> 3\sigma$ confidence) Balmer decrement, or $[O III]$ line flux, could not be determined. The double power-law dust correction (Equation 3) is applied in these figures.

We now ask the question: given the broad range in star formation rate and star formation history, in which bulges is the majority of current black hole growth occurring? The result is shown in Figure 14a, where each histogram bin in the plot represents the volume-integrated dust-corrected $[O III]$ luminosity of the bulges contained within each 0.1×0.1 PC1 \times PC2 pixel, smoothed to the same binning as in the other panels of the figure. Despite the large range in the number density of bulges per pixel across this diagram (see Figure 13b), the total AGN luminosity is distributed fairly uniformly across bulges with all types of star-forming stellar population. A decrease is seen in the quiescent bulges, despite their large numbers, and also in the strongly starbursting objects. We will return to a more quantitative analysis of the total and mean $[O III]$ luminosities of each population shortly.

Next, we ask the question: what type of star formation history is associated with the highest mean rate of black hole growth? Figure 14b indicates the mean AGN $[O III]$ luminosity divided by black

hole mass in each bin (using σ_v^4 as a proxy for black hole mass and applying a volume weighting as usual). Thus the colourscale coding represents the mean growth rate of black holes (in Eddington units). It is clear that *on average AGN grow most strongly, i.e. have high accretion rates, in host bulges which follow the strong starburst trajectory, from starburst to post-starburst*. As we saw in the last section, objects lying in this region of PC space are also more likely to show evidence of morphological disturbance, certainly strongly suggestive of a connection between black hole growth, the growth of the stellar bulge and perturbation of the gravitational potential by external forces.

While the bulges lying along the starburst/post-starburst trajectory have the highest mean black hole growth rates, they are relatively few in number. Overplotted in Figure 14b as red points are the 207 bulges with the highest ratios of $[O III]$ luminosity to black hole mass. Using the more conservative double power-law dust attenuation correction, these systems taken together contribute half of the total volume-integrated black hole accretion rate of our entire sample of over 33,000 bulges! It can be seen that these are in fact distributed fairly evenly across the whole population of young bulges, with 75% lying in the star-forming class, 8% in the starbursts and 9% in the post-starbursts. In numbers they account for 7% of the bulges star-forming bulges, 15% of the post-starbursts and 29% of the starbursts. In summary *a strong recent or ongoing*

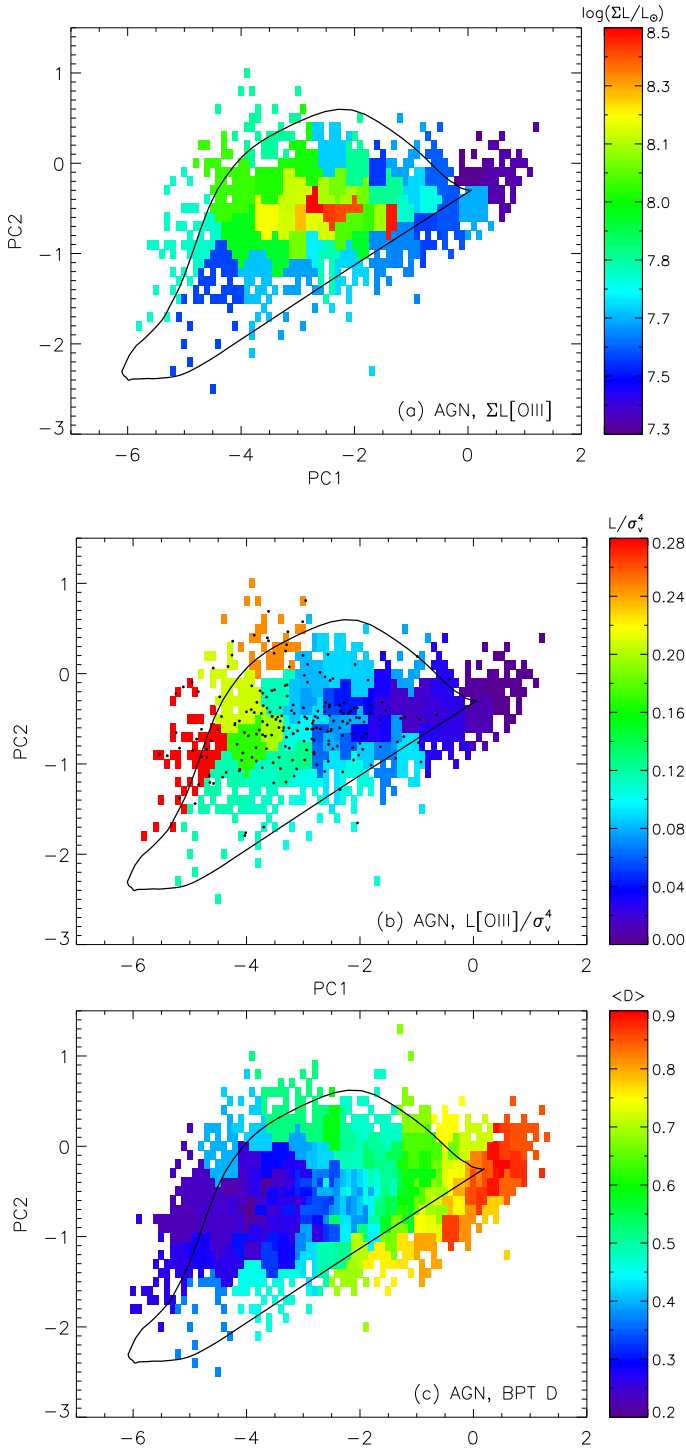


Figure 14. *Top:* The volume-weighted total dust-attenuation-corrected [O III] luminosity of the AGN in each joint 0.1×0.1 PC1 \times PC2 histogram pixel, smoothed onto the same adaptive bins as figures *b* and *c*. The colour scale indicates the logarithm of the total luminosity. All luminosities are measured in solar units. *Middle:* The volume-weighted mean dust-corrected [O III] luminosity normalised by σ_v^4 in each bin. The black points indicate the positions of the galaxy bulges with the highest accretion rates, which taken together account for 50% of the total accretion rate of our entire sample. *Bottom:* The distance of each system away from the star formation locus in the BPT diagram. LINERs and Seyferts are found at large *D*, composite objects at smaller *D*. A single weak instantaneous burst track of 1% burst fraction is overplotted. In both the top and center panels, the double power-law dust correction has been used (Equation 3).

starburst within a bulge is a helpful, but not necessary, condition to feed a strongly accreting AGN.

Putting the results of Figures 14*a* and *b* together we can see a new aspect of the fact that the growth of black holes in the present day Universe is spread broadly over all [O III] luminosities i.e. there are many weak [O III] systems and fewer strong [O III] systems, but all contribute significantly to the overall growth of black holes today (Heckman et al. 2004; Hao et al. 2005). We add to this result by showing that *the growth of black holes today is spread widely over bulges with all types of recent star formation history*, with the few strong [O III] systems existing in the rarer strong starburst and post-starburst bulges, and the weak [O III] systems arising in the more common bulges with weaker star formation. In the following subsection we will present these results quantitatively.

Finally, Figure 14*c* shows the mean distance of objects away from the star-forming locus on the BPT diagram (*D*, see Kauffmann et al. 2003a), where composite objects have low *D* and Seyferts and LINERs have larger *D*; the transition from composite objects into pure-AGN dominated objects occurs at around $D=0.7$. Again, strong trends with stellar population of the bulge are evident in the sense that the AGN hosted by quiescent and post-starburst bulges have emission line ratios which place them further into the LINER and Seyfert class, and bulges with even moderately young stellar populations host AGN predominantly classified as composite objects. For a recent study of the host galaxy properties of AGN in the SDSS as a function of emission line classification see Kewley et al. (2006). While it is clear that the post-starburst bulges are on average more “AGN-like” in their emission lines than galaxies with the same 4000\AA break strength, it is not currently clear whether this can be explained entirely by the reduced contribution of ongoing star formation.

7.4.2 AGN luminosity and the importance of dust correction

We now look more quantitatively at the total [O III] luminosity contributed by AGN in bulges with different recent star formation histories, splitting the bulge sample into the stellar population subclasses defined in Section 7.⁶

In the top panels of Figure 15 the total [O III] luminosity of AGN contained in each class of galaxy bulge is plotted, before and after correcting the [O III] flux for dust attenuation; the results are also given in Table 2. All results are shown for the two dust laws given in Section 2.1.1 and in the following text results are given first for the single power-law dust attenuation correction, and in brackets for the double power-law correction. We note that although the general trends in our results are not changed by which dust law we use, the absolute values of the mean [O III] luminosities are considerably different. Objects without the requisite lines with which

⁶ At this point it is necessary to discuss the contamination of the [O III] emission by star formation. Can our results be taken as reliable indicators of the relative amount of AGN activity occurring in galaxies as a function of recent bulge star formation history? Our worst affected class of bulges will clearly be the starbursts, however even in this class, the mean [O III] luminosity in those objects classified as having emission lines predominantly originating from star formation is more than a factor of three lower than in those objects classified as composite objects or pure AGN. The contribution by star formation to the [O III] luminosities of objects classified as AGN can thus be expected to be small on average. On the other hand, relatively weak AGN in bulges with very high star formation rates may not be recognised as such. In this case the contribution to the overall growth of black holes in the starburst class may be an underestimate.

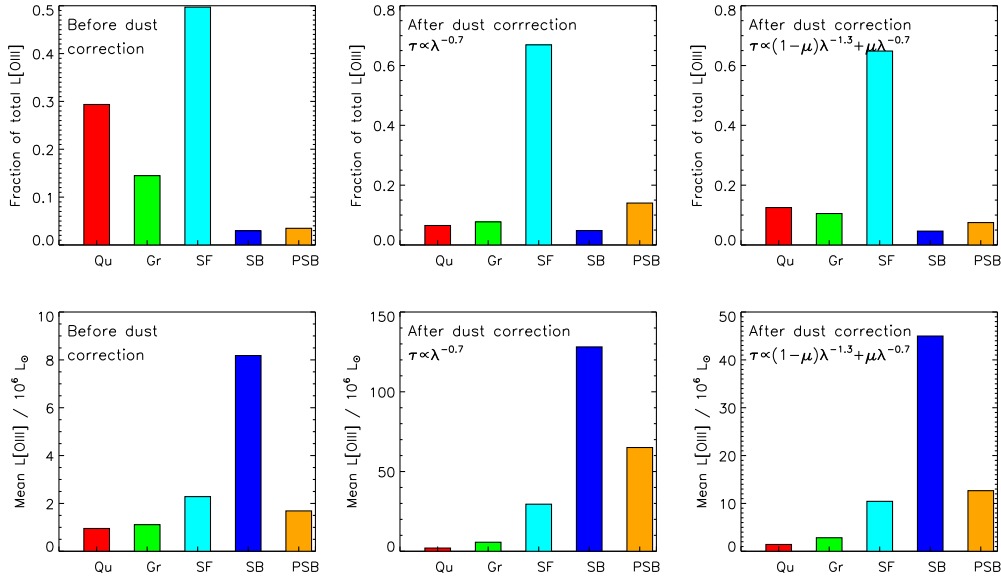


Figure 15. The total (volume-integrated)(*top*) and mean (*bottom*) [O III] luminosity of AGN hosted by different classes of bulges, before (*left*) and after (*center* and *right*) correction of the [O III] flux for attenuation by dust. The dust corrected results are shown for the two different attenuation laws discussed in Section 2.1. The classes are labelled as: **Qu** quiescent; **Gr** green-valley; **SF** star-forming; **SB** starburst; **PSB** post-starburst. The results are also presented in Table 2.

Table 2. The fraction (F) of the total volume-integrated, and mean [O III] luminosity of AGN hosted by each class of bulge, before (*uncor*) and after (*cor*) correction of the [O III] line flux for attenuation by dust. Luminosities are given in solar units. The final column gives the fraction of objects in each class for which Balmer decrements are measured, and therefore their [O III] luminosities can be corrected for dust attenuation. All values have been corrected for survey volume effects using the $1/V_{\max}$ method (see Section 2).

class	$F(L_{\text{uncor}})$	$\log\langle(L_{\text{uncor}})\rangle$	$F(L_{\text{cor}})^a$	$\log\langle(L_{\text{cor}})\rangle^a$	$F(L_{\text{cor}})^b$	$\log\langle(L_{\text{cor}})\rangle^b$	fraction
Quiescent	0.28	5.98	0.06	6.31	0.12	6.15	0.08
Green Valley	0.14	6.05	0.07	6.75	0.10	6.45	0.20
Star forming	0.47	6.36	0.65	7.47	0.62	7.02	0.61
Starburst	0.03	6.91	0.05	8.11	0.04	7.65	0.96
Post-starburst	0.03	6.23	0.14	7.81	0.07	7.10	0.35

^a Using a single $\lambda^{-0.7}$ power-law dust attenuation correction.

^b Using a double power-law dust attenuation correction to account for differing attenuations in the birth clouds and ISM (Equation 3).

to calculate the dust attenuation are included in the integral without any dust correction; this will cause a small underestimation of the total dust corrected [O III] luminosity in most classes as discussed in Section 2.1.1 (the fraction of objects with dust corrections are given in Table 2). There are two main results. Firstly we can see that all classes of galaxy bulges are important contributors to the volume-integrated AGN [O III] luminosity of our sample, although clearly the ordinary star-forming class dominates the budget. Secondly, due to the trend of increasing dust content with increasing star formation *our perception of the relative importance of AGN hosted by each class of bulge is greatly affected by the inclusion of the dust correction.*

In particular the AGN hosted in post-starburst bulges are most affected by the dust correction, changing their position in the volume-integrated [O III] budget from relatively unimportant to contributing at a similar level to the other minority classes, despite their small numbers. Careful investigation of the spectral fits shows that this is not caused by a systematic problem with our emission line measures in objects with strong Balmer absorption, however

we find that more than 30% (almost 20% for the double power-law dust correction) of the final dust corrected [O III] luminosity contributed by AGN in post-starburst bulges arises from 13 objects with observed $H\alpha$ to $H\beta$ flux ratio greater than ~ 8.6 , corresponding to an optical depth in the V-band (τ_V) of $\gtrsim 5.3$ ($\gtrsim 3.3$ for the double power-law dust correction). At these attenuations small errors on the Balmer decrements can lead to significant absolute errors on the total luminosities, and the form of the dust law used becomes crucial. Additionally, more than 50% of the post-starburst bulges are not corrected for dust attenuation before being included in the calculation of total [O III] luminosity, primarily due to insufficient SNR or flux in the $H\beta$ emission line to accurately determine their Balmer decrements. It is entirely plausible that these would also contribute significantly were we able to measure their dust contents. Ideally, follow-up IR observation is required to identify the true dust contents of these objects, and therefore their true contribution to the global volume-integrated [O III] luminosity of type 2 AGN (see Section 8.3).

The bottom panels of Figure 15 show the mean [O III] lumi-

nosity arising from AGN in each class of bulge. Again, the huge difference in the post-starburst systems before and after dust correction is notable. It is also notable that *AGN contained within the starburst and post-starburst bulges have the highest mean [O III] luminosity, after dust correction, of the entire sample.* It is important to note that the mean luminosity of the post-starbursts should be taken as lower limits, due to those objects we are unable to correct for dust attenuation, and the mean luminosity of the starbursts should be taken as upper limits, due to contamination by star formation.

8 DISCUSSION

The distribution of stellar populations of galaxy bulges in the 2-dimensional space of 4000Å break strength and Balmer absorption line strength is qualitatively well described by a burst scenario, with a mixture of brief, strong bursts and longer lived or more frequent weak bursts causing about half of the bulges to show signs of on-going or recent star formation. In the future, a full comparison with model galaxy populations will allow us to understand more fully the physical processes and timescales involved.

Here we have concentrated on the morphological, dust and AGN properties of galaxies in different regions of 4000Å break strength and Balmer absorption line strength space. In this section we will firstly review and collate the main observational findings presented in the preceding sections, focussing on those galaxy bulges with ongoing or recent star formation. We will then summarise and discuss the main conclusions with respect to the build up of black hole mass in the local Universe and the nature of the post-starburst bulges. Finally, we will briefly discuss the possibility of breaking the well known burst age - burst strength degeneracy.

8.1 Summary of observational results

Figure 16 summarises the properties of our sample and our results, comparing the distributions of physical properties of galaxies with star-forming, starbursting and post-starburst stellar populations in their bulges.

The classical indices $D_n(4000)$ and $H\delta_A$: The post-starburst class has a similar $D_n(4000)$ distribution to the star-forming class, and therefore would be judged to have similar mean stellar ages using $D_n(4000)$ alone. Our classification of objects as “post-starburst” is very different to previous studies, as can be seen from the distribution of $H\delta_A$ (only objects with $H\delta_A$ measured with $\text{SNR} > 3$ are included). Instead of applying a straight cut on Balmer line equivalent width, we identify them as having excess Balmer absorption for a given $D_n(4000)$, allowing us to identify weaker and older bursts.

$H\alpha$ luminosity and Specific SFR: The sequence in $D_n(4000)$ is simply a sequence in specific SFR of the galaxy. Those post-starburst galaxies with measured $H\alpha$ emission lines have specific star formation rates covering the range of the starforming class. However, only $\sim 40\%$ of the total post-starburst sample are shown in this figure: a large fraction of the remainder can not be corrected for dust attenuation due to very weak $H\beta$ lines.

Stellar mass and stellar surface mass density: The post-starburst and starforming classes are hosted by galaxies with similar stellar mass distributions, with the starburst class having a slightly lower mean stellar mass enclosed within the fibre. Our sample was defined to have $\mu_* > 3 \times 10^8 \text{ M}_\odot \text{ kpc}^{-2}$, and we can see a tail to higher stellar surface mass densities for post-starburst hosts,

implying smaller z -band radii. This may be an indication of recent major mergers in a proportion of this class: simulations of dissipational (gas-rich) mergers suggest that remnants are more compact than the originating galaxies.

Concentration and lopsidedness: are both global properties measured from SDSS photometry. The starforming and starburst bulges live in galaxies with a similar distribution of mean concentration, although Figure 11 does show a trend of decreasing concentration with decreasing PC1 within the starforming class alone. The “lopsidedness” of the light distribution is an important indication of recent gravitational disturbance. Although all the distributions are broad, both the starbursts and post-starbursts show a higher mean lopsidedness in their light distributions. Such effects are expected to be identifiable in merger remnants for of-order a gigayear, in line with the likely ages of our post-starburst stellar populations.

Attenuation by dust of stellar continuum light and nebular emission lines: It is already well known that both measures of dust content in SDSS galaxies are well correlated, although with large scatter, and there is a strong correlation between dust content and star formation rate. We find strong trends in attenuation of continuum light with stellar population, best viewed in the 2D histogram of Figure 12a. The post-starburst galaxy bulges have a much broader distribution of dust contents than the star-forming and star-bursting classes, in particular, a large fraction show very large Balmer decrements which impacts greatly on their inferred star formation rates and AGN accretion rates.

[O III] emission luminosity: While the majority of type 2 AGN reside in quiescent galaxies, these are in general the least luminous, with low accretion rates. Those with high accretion rates are hosted by galaxies with younger stellar populations. After correcting for attenuation by dust, we find that AGN hosted by the post-starburst and starburst bulges have the highest mean [O III] luminosities and, despite their smaller numbers (3.5% of the entire AGN sample), contribute significantly to the total volume-integrated AGN [O III] luminosity of the local Universe (~ 10 –20% depending on the dust correction used). On the other hand, the strongest accreting black holes are hosted by bulges with all types of recent star formation activity, not just those which lie on the evolution tracks of strong starbursts.

8.2 Black hole accretion and build-up of the stellar bulge

Clearly, an outstanding question in astrophysics today is the physical mechanisms responsible for the M - σ relation for black holes and bulges. Our main conclusions relating to the recent star formation histories of galaxy bulges and the properties of the black holes they contain are as follows:

- Due to the trend of increasing dust content with increasing star formation rate, the effect of dust attenuation of the [O III] line impacts significantly on our estimation of which galaxies host the most rapidly growing black holes.
- AGN reside in galaxy bulges which have experienced a wide variety of recent star formation histories. The quiescent host bulges are the most numerous, containing 45% of all AGN. However, these are AGN with the lowest mean [O III] luminosities. The bulges lying on the strong starburst track (starbursts through post-starbursts, burst mass fractions $\gtrsim 1\%$) are the least numerous, but have highest mean dust corrected AGN [O III] luminosities (Fig 15).
- Putting these results together, and integrating the rate of black hole growth over our sample, we find that most ($\sim 80\%$) of this growth is occurring in bulges with substantial recent or on-going

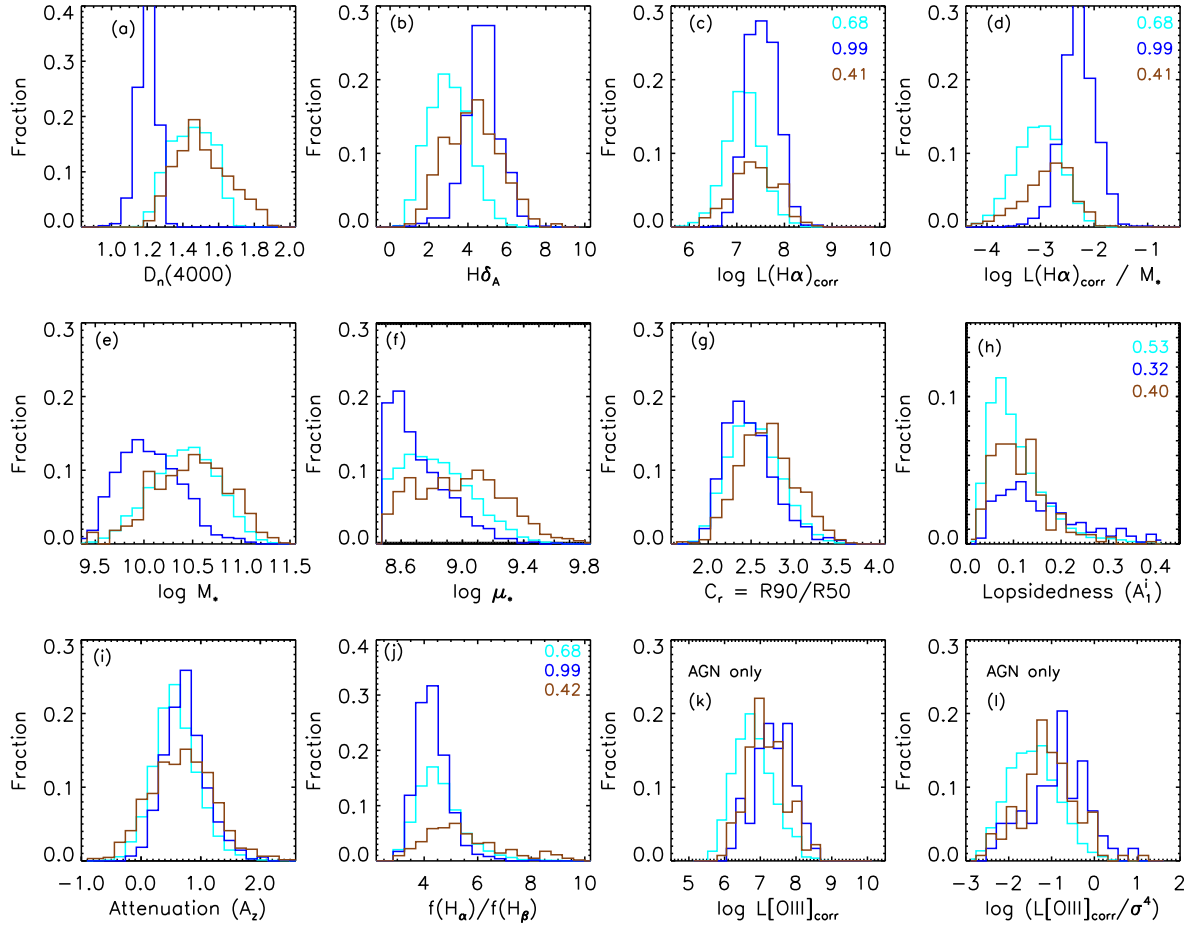


Figure 16. The distribution of selected spectral parameters, global photometric parameters and derived physical properties for bulges with star-forming (cyan), starburst (blue) and post-starburst (brown) stellar populations as classified through our spectral analysis of the stellar continuum. (a) 4000Å break strength ($D_n(4000)/\text{mag}$); (b) $H\delta$ absorption line strength ($H\delta_A/\text{\AA}$); (c) dust attenuation corrected $H\alpha$ luminosity, for those objects with significant $H\alpha$ and $H\beta$ fluxes (L_\odot); (d) dust attenuation corrected $H\alpha$ luminosity, normalised by the stellar mass of the galaxy; (e) stellar mass (M_*/M_\odot); (f) stellar surface mass density ($\mu_*/M_\odot \text{ kpc}^{-2}$); (g) r -band concentration (C_r); (h) i -band lopsidedness of global light distribution (A_1^i); (i) z -band attenuation measured from continuum light (A_z/mag); (j) the Balmer decrement - flux ratio of $H\alpha$ to $H\beta$; (k) dust attenuation corrected $[O III]$ luminosity for only those objects classified as AGN (pure AGN or Composites) from their narrow emission line ratios (L_\odot); (l) $[O III]$ luminosity normalised by stellar velocity dispersion to the power four, a proxy for black hole accretion rate relative to the Eddington limit ($L_\odot \text{ km}^4 \text{ s}^{-4}$). All emission line dust attenuation corrections in this plot use the double power-law attenuation law in Equation 3.

star formation. However, the majority of this growth occurs in the star-forming class, which show no evidence for recent major changes in their star formation rate.

- At least half of the total volume-integrated AGN $[O III]$ luminosity is contributed by 207 bulges (0.5% of our total bulge sample). These are found in bulges that lie in the ordinary star-forming region, as well as along the strong starburst track. They account for 7% of the star-forming bulges, 15% of the post-starburst bulges and 29% of the starbursts.

- We therefore conclude that a strong recent or ongoing central starburst (possibly fuelled by a tidally-induced inflow of gas) is a helpful, but not necessary condition for the build up of black holes in the present-day universe.

The coincidence along the strong starburst track of enhanced disturbance of the global morphologies of the galaxies and increased black hole accretion rates, provides strong circumstantial

evidence for a merger induced starburst–, or post-starburst–, AGN connection. A full analysis will be the subject of the future paper.

8.3 The nature of bulges with excess Balmer line absorption

In this paper we have developed a specific methodology for recognizing galaxies that are undergoing or have undergone an intense episode of star formation. Our method differs from most of those used in the past. At the close of the paper, we will attempt to put our method and its results into the framework of these previous studies. Some of these previous studies have emphasised the effect that heavy dust attenuation can have on the interpretation of the star formation history of bursty galaxies. We will examine this issue below. Finally, we will briefly comment on the possibility of breaking the degeneracy between the time since the starburst and its strength.

8.3.1 The post-starburst galaxy zoo

As with many aspects of astronomy, the different classifications of similar objects used by different authors can lead to confusion. Here we summarise the different aspects of defining a post-starburst sample, with respect to the results presented in this paper.

All the extant methods for recognizing post-starbursts make use of the unique signature provided by the stellar Balmer absorption lines. The strength of these lines is not a monotonic function of time following a burst of star formation: rather, these lines are strongest in A-type stars which have main sequence lifetimes of ~ 0.1 to 1.0 gigayears. Traditionally, this “chronometer” has been combined with a measure of the strength of the nebular emission-lines (typically $H\alpha$ or $[O II]$). These are excited by O stars, which have a lifetime of only about seven million years. Thus, the traditional definition of a post-starburst (strong Balmer absorption-lines and weak nebular emission-lines) is quite sensitive to even relatively young post-starbursts.

Our classification scheme deliberately selects objects in a different way. First and foremost, we place no restriction on emission-line strengths, as this would remove all but the weakest emission-line AGN from our sample (Yan et al. 2006). This has paid big dividends. We have shown that at least 56% of our post-starburst galaxies host AGN, and that these are (on-average) the most luminous AGN in our sample. Preferentially selecting against those galaxies with strong AGN will lead to a much reduced sample and potentially different conclusions. Selection based on weak emission lines also prevents the possibility of selecting objects undergoing multiple, relatively closely spaced starbursts. For example, Brinchmann et al. (2004) found that low mass galaxies classified as post-starbursts based on $D4000$ vs. $H\delta_A$ had *stronger* $H\alpha$ emission-lines (indicating higher current star-formation rates). Thus, whole sub-classes of objects undergoing similar processes may be missed by a cut based on weak emission-lines.

It is also important to point out that we do not select strictly on the basis of the Balmer absorption-lines. Instead we require that post-starbursts have *stronger Balmer lines than expected based on their 4000Å break strength*. This latter monotonically and slowly increases with time after a burst. This allows us to retain AGN and to select much older post-starbursts, up until the point at which they return to the green-valley/quiescent population at an age of ~ 1 -2 Gyr. In fact, Figure 16b shows that the post-starburst class exhibits a broad range in $H\delta_A$. This figure also clearly shows that the starburst class has a similar (though narrower) distribution in $H\delta_A$ as the post-starbursts. The difference in our selection method lies in the fact that a straight cut on Balmer absorption-line strength preferentially selects young starbursts, while our method is still quite sensitive to older systems. This can be seen clearly in Figure 7, where a straight cut on $H\delta_A$ leads to a very different coverage of the burst tracks than our method.

The disadvantage of our scheme of not selecting on emission lines is that it is relatively insensitive to *young* post-starbursts. These lie in the same region of $PC1$ vs. $PC2$ and $D_n(4000)$ vs $H\delta_A$ as young star-forming galaxies. Thus, it is important to recognise that some of the bulges that we classify as starbursts may actually be young post-starbursts.

8.3.2 The stellar populations of dusty starbursts

An intriguing property of our sample of post-starburst galaxies is their high average Balmer decrements, indicating very high dust contents (see Figure 12). Figure B6 presents images of some of the

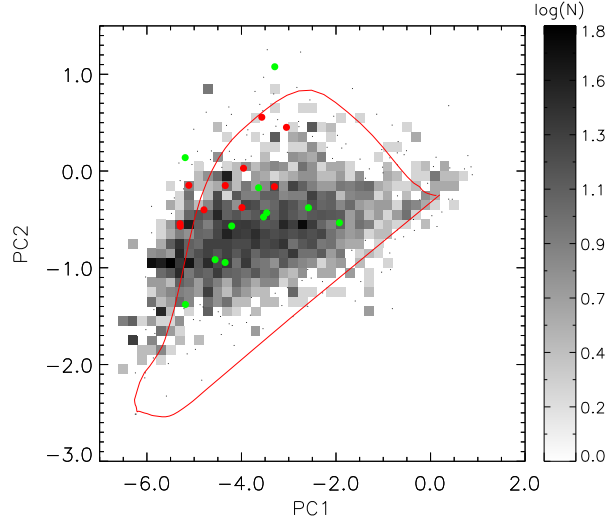


Figure 17. Joint number distribution of $PC1$ and $PC2$ for SDSS galaxies with $0.01 < z < 0.07$ and counterparts in the IRAS Faint Source Catalogue. In regions of low number density, individual points are plotted. To guide the eye, the same single weak instantaneous burst track is overplotted as in Figure 13. The filled circles are VLIRGS with $\log L_{FIR}/L_{\odot} > 11.26$ ($H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$), the red points would be classified as e(a) galaxies by (Poggianti & Wu 2000).

dustiest post-starburst galaxies; a comparison with Figure B5 gives the impression that they are certainly redder, some with clear dust lanes.

The apparently large amount of dust attenuation makes it difficult to obtain a clear and accurate picture of their true nature using optical data alone, especially given the large uncertainty in the slope of the dust attenuation curve at high optical depths. Strong Balmer absorption lines imply an excess of A stars visible relative to the slightly younger and hotter O and B stars. It does not necessarily imply no O or B stars are present, for example heavily dust enshrouded starbursts have been suggested as an explanation for the strong high-order Balmer absorption-lines seen in many galaxies that are luminous in the far-infrared (Smail et al. 1999; Poggianti & Wu 2000; Miller & Owen 2001). This explanation may at first glance appear to fit well with the high dust contents of our objects.

To test this possibility, we turn to a sample of SDSS galaxies detected in the far-infrared (FIR) with the IRAS satellite. Note that in this sample, no restriction has been placed on stellar surface mass density of the galaxies, so these results pertain to the stellar populations of the bulges of all FIR bright galaxies with optical counterparts in the SDSS and in the redshift range $0.01 < z < 0.07$.

We use the same matched sample as described in Pasquali et al. (2005), but for SDSS DR4, which includes 3008 main DR4 galaxies with $0.01 < z < 0.07$, SDSS spectral $SNR_g > 8$ and detected $60\mu\text{m}$ flux. A further 56 galaxies are removed during the PCA, due to poor quality spectra, leaving a final sample of 2952 galaxies. Figure 17 presents the joint $PC1/PC2$ distribution of the galaxies; overplotted is the same weak starburst track as in previous figures. According to our classification scheme, we find that the central regions of IRAS bright galaxies have predominantly starforming and starbursting stellar populations (82%). Only 5% of them are found in the post-starburst class and only 9% have quiescent or green-valley populations.

We focus in particular on the extreme IR bright objects in

our sample, those classified as Very Luminous Infrared Galaxies (VLIRGS) by Wu et al. (1998) and Poggianti & Wu (2000). Converting their FIR luminosity cut to our cosmology selects 21 objects with $\log(L_{\text{FIR}}/L_{\odot}) > 11.26$ ($H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$), where L_{FIR} is defined in Pasquali et al. (2005, Section 2.2). The position of these objects are overplotted as filled circles in Figure 17 and we note immediately that VLIRGS are found in galaxies with all varieties of ongoing star formation.

Poggianti & Wu (2000) find that 56% of VLIRGS show strong H δ absorption (equivalent width $> 4\text{\AA}$), but also strong [O II] emission (equivalent width $> 5\text{\AA}$). They classify these galaxies as “e(a)”, and interpret them as dusty starbursts in which the contribution of OB stars to the optical spectra is greatly reduced by dust-obscuration of the youngest stars. Repeating this analysis for the 21 VLIRGS in our sample, we find 10/21 e(a) galaxies, in agreement with their results; these are plotted as red circles in Figure 17. We note immediately that these lie in a very different region of the diagram to our post-starburst galaxies. With respect to the instantaneous burst track, they are considerably younger than our post-starburst class; in our classification scheme they would actually lie in the starburst or starforming class, fitting nicely with the results of Balogh et al. (2005) that e(a) galaxies are predominantly disk galaxies and may indeed be dusty starbursts.

8.3.3 The IRAS properties of the post-starbursts

We have also used the IRAS Faint Source Catalog to characterise the FIR luminosities of our sample of post-starburst bulges. While we find that the fraction of post-starbursts with $60\mu\text{m}$ IRAS detections increases with increasing Balmer decrement, the median value for the implied FIR luminosity is only $10^{10.4} L_{\odot}$, and only $10^{10.5} L_{\odot}$ for the $\sim 10\%$ of FIR-detected post-starburst bulges with the steepest Balmer decrements. This is significantly lower than the median value of $10^{11.1}$ for the VLIRGs.

We conclude that our dusty post-starbursts are significantly different from the VLIRGs studied by Poggianti & Wu (2000). Our objects have an older mean age (less negative values of PC1), a significantly greater excess in the strength of the Balmer absorption-lines relative to typical galaxies of this age (larger PC2), and substantially lower FIR luminosities (lower implied star formation rates). We therefore believe that our objects are bona fide post-starbursts. The true cause of the high Balmer decrements awaits follow-up infra-red observations, combined with detailed modelling of the dust distribution in galaxies, including in particular AGB stars.

8.3.4 Strong and old, or weak and young bursts?

The first step required to really constrain the causal connection between the central starbursts and the strong AGN signatures is to break the degeneracy between the age of the last burst of star formation (strictly the time since the starburst switched off) and the mass of stars formed in the burst. In Figure 7 we showed how this may be achieved using our third index, excess Ca II (H&K) absorption. These absorption lines have been introduced before by Leonardi & Rose (1996) as a promising age diagnostic of bursts, however due to the SNR required for their index, it is not applicable generally to SDSS spectra. Taking Figure 7 at face value would suggest that there are a number of bulges with strong Ca II absorption which must be caused by very old, strong bursts. Tracing the tracks back in PC1/2 would indicate that the progenitors of such systems are not contained within the SDSS sample.

However, it is premature to draw such a conclusion for several reasons. Firstly, as discussed in Section 6.1, the BC03 stellar population models show a systematic offset from the SDSS data in 4000\AA break strength. As explained in Section 6.1 the first PCA component contains the primary correlation between 4000\AA break strength, Balmer line strength and Ca II absorption line strength (see Figure 2: all three spectral features are visible in the first eigen-spectrum). Therefore, on fitting the correct 4000\AA break strength the first component reproduces the wrong absorption line strengths, forcing the second and third components to compensate. This could cause a systematic offset in PC3 and lead to the mistaken conclusion that the bursts are stronger than in reality.

Secondly, the instantaneous burst model is almost certainly a gross over simplification of the true recent star formation history of the bulges. We are now reaching the stage in galaxy spectral analysis where models with a physically motivated star formation history are required. By combining the next generation of accurate spectral synthesis models with numerical simulations of galaxy mergers, bar instabilities and the interaction of galaxies with the intercluster medium, and accurate number counts provided by simulations within a cosmological framework, the analysis of galaxy spectra to determine precise star formation histories will provide strong constraints on the physical processes driving the inflow of gas onto black holes, and the relative importance of star formation and black hole feedback in the evolution of galaxies.

9 FINAL THOUGHTS

The huge number of high quality galaxy spectra now available to us with surveys such as the SDSS, allow unprecedented statistical studies of the properties of galaxies. Until relatively recently, both samples and the spectral regions observed were small, making difficult analyses which are now routine, such as measurement of the Balmer decrement to correct emission lines for dust attenuation. With such large quantities of high quality data, some form of data compression is necessary in order to cope. However, the simple extraction of small regions with which we are familiar - such as the Lick indices - may be a poor way to make full use of all the information now available to us. Now is the time in which statistical techniques applied to spectra, such as the one presented in this paper, can provide useful additional constraints on the physical processes underlying the galaxy spectra. Of course, as more sensitive techniques are studied new problems will be found with the models, but these are rarely a cause for halting such studies.

We have developed a new set of indices specifically designed for investigating the very recent star formation histories of galaxies, and applied them to the bulges of low redshift galaxies in the SDSS. The indices are general, however, and may easily be applied to other datasets. In this paper, we have focussed on qualitative trends of global morphology, dust and AGN properties with bulge stellar population in the low redshift Universe, showing how new trends can be uncovered by simply using more sensitive techniques for measuring stellar populations from galaxy spectra. In the future we will be able to compare results such as these directly to theoretical models, using spectra calculated during detailed simulations of galaxy mergers and semi-analytic simulations of galaxy populations within the cosmological framework. Such comparisons will allow us to investigate, for example, the relative importance of truncation of star formation and short starbursts in galaxies in clusters, of weak starbursts on the mass build up galaxy bulges, and of

the quenching of star formation in bulges due to AGN feedback, some of the key questions in galaxy evolution today.

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APPENDIX A: PRINCIPAL COMPONENT ANALYSIS

The standard formalism of PCA presented here is compiled from Kendall (1975), Efsthathiou & Fall (1984) and Murtagh & Heck (1987). In all that follows vectors are represented by a single underscore, 2-dimensional matrices by a double underscore.

Firstly, the “mean spectrum” is subtracted from all input spectra. This is not a necessary requirement for PCA, and often not applied (e.g. Connolly et al. 1995), however it removes the requirement for the first component to point in the direction of the mean spectrum which, due to the orthogonality constraint of PCA, affects subsequent components.

The N mean subtracted spectra each M pixels long are placed in a data array \underline{X} with elements X_{ij} , where $1 \leq i \leq N$, $1 \leq j \leq M$. The elements of the covariance matrix (\underline{C}) of this data array are given by:

$$C_{jk} = \frac{1}{N} \sum_{i=1}^N X_{ij} X_{ik}. \quad (A1)$$

The covariance matrix can be decomposed into an eigenbasis, described by a set of eigenvectors ($\{\underline{e}\}$, principal components in the language of this paper, also referred to as eigenspectra) each M pixels long :

$$\underline{C}\underline{e}_j = \lambda_j \underline{e}_j \quad (A2)$$

where λ_j are the eigenvalues and j identifies the eigenvector. Note that these are orthogonal unit vectors:

$$\underline{e}_j^T \underline{e}_k \equiv \sum_i e_{ji} e_{ki} = \delta_{jk} \quad (A3)$$

where T represents the transpose. It can be shown that \underline{e}_1 is the axis along which the variance is maximal, \underline{e}_2 is the axis with the second greatest variance, and so on until \underline{e}_M has the least variance. The principal

component amplitudes for each input spectrum \underline{f} are given by

$$a_j = \underline{f}^T \underline{e}_j. \quad (A4)$$

Reconstruction of the spectrum is achieved by multiplying the principal component amplitudes by their respective eigenvectors:

$$\underline{f} = \sum_{j=1}^M a_j \underline{e}_j. \quad (\text{A5})$$

In general as the variance of the eigenvectors decrease, so does the useful information contained in the spectra, hence making PCA a useful form of data compression: in equation (A5) we would sum from $j = 1$ to m where $m \ll M$, hence reducing the dimensionality of each spectrum from N to m . The exact number of eigenvectors required to reconstruct the input spectrum is unconstrained, and decided upon based on the dataset and purpose of analysis. The M or m eigenvectors can be used as a basis set upon which to project *any* spectrum (\underline{f}) of the same dimensions. The reconstructed spectrum only contains information present in the eigenvectors, which may not be a fair representation of the spectrum if the spectrum were not used during creation of the eigenvectors and/or fewer than M eigenvectors are used during reconstruction.

APPENDIX B: EXAMPLE SDSS IMAGES

Figure B1. Quiescent: Example SDSS postage stamp images of galaxies whose bulge stellar populations are old i.e. are part of the red sequence, quiescent cloud in PC parameter space. Each image is 1 arcmin square and PC1 and PC2 values are given at the bottom. The approximate size of an SDSS spectroscopic fibre is indicated in the top left corner. Only galaxies with $z < 0.05$ have been selected.

Figure B2. Green-valley: Same as Figure B1 for galaxies with slightly younger bulge stellar populations (smaller $D_n(4000)$ or PC1) than those in the red sequence – so-called “green-valley” objects.

Figure B3. Star-forming: Same as Figure B1 for galaxies with star forming bulges, with intermediate $D_n(4000)$ or PC1. They are ordered by increasing PC1.

Figure B4. Starburst: Same as Figure B1 for galaxies with bulges dominated by light from young O and B stars. Both PC1 and PC2 are small, indicating a very weak 4000Å break and weak Balmer absorption lines.

Figure B5. Post-starburst: Same as Figure B1 for galaxies with excess Balmer absorption lines over that expected for their 4000Å break strength.

Figure B6. Dusty objects: Same as Figure B1 for galaxies with excess Balmer absorption lines over that expected for their 4000Å break strength and $H\alpha$ to $H\beta$ flux ratios greater than > 8.6 . Galaxies at all redshifts are included (i.e. $0.01 < z < 0.07$).

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