Post-starburst galaxies: more than just an interesting curiosity

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ABSTRACT

From the VIMOS VLT Deep Survey (VVDS), we select a sample of 16 galaxies with spectra which identify them as having recently undergone a strong starburst and subsequent fast quenching of star formation. These post-starburst galaxies lie in the redshift range 0.5 < z < 1.0 with masses > 10^{9.75} M⊙. They have a number density of 1 × 10^{-4} Mpc^{-3}, almost two orders of magnitude sparser than the full galaxy population with the same mass limit. We compare with simulations to show that the galaxies are consistent with being the descendants of gas-rich major mergers. Starburst mass fractions must be larger than ~5–10 per cent and decay times shorter than ~10^8 yr for post-starburst (PSB) spectral signatures to be observed in the simulations. We find that the presence of black hole feedback does not greatly affect the evolution of the simulated merger remnants through the PSB phase. The multiwavelength spectral energy distributions of the PSB galaxies show that 5/16 have completely ceased the formation of new stars. These five galaxies correspond to a mass flux entering the red-sequence of \dot{\rho}_{A→Q,PSB} = 0.0038_{-0.001}^{+0.0004} M⊙ Mpc^{-3} yr^{-1}, assuming the defining spectroscopic features are detectable for 0.35 Gyr. If the galaxies subsequently remain on the red sequence, this accounts for 38_{-11}^{+4} per cent of the growth rate of the red sequence. Finally, we compare our high-redshift results with a sample of galaxies with 0.05 < z < 0.1 observed in the Sloan Digital Sky Survey and United Kingdom Infrared Telescope Infrared Deep Survey. We find a very strong redshift evolution: the mass density of strong PSB galaxies is 230 times lower at z ~ 0.07 than at z ~ 0.7.

Key words: methods: statistical – galaxies: evolution – galaxies: high redshift – galaxies: stellar content.

1 INTRODUCTION

Since Hubble (1926), the bimodality in the distribution of galaxy properties has been one of the great curiosities in the field of astronomy. Bimodality is observed in galaxy colours, morphology, star formation rates and galaxy stellar masses. Modern spectroscopic galaxy surveys have allowed us to quantify the bimodality precisely, especially with the advent of the Sloan Digital Sky Survey (SDSS) (Strateva et al. 2001; Kauffmann et al. 2003b; Baldry et al. 2004). Even at high redshift, evidence for bimodality in the galaxy population is being sought and found (Bundy, Ellis & Conselice 2005; Willmer et al. 2006; Franzetti et al. 2007).

Recent observations have revealed that since a redshift of around unity the total mass of stars living in red-sequence galaxies has increased by a factor of 2 (Bell et al. 2004). At the same time, the stellar mass density of the blue sequence has remained almost constant. The interpretation is that some blue galaxies migrate on to the red sequence after the quenching of their star formation, whilst the remainder continue to form new stars (e.g. Arnouts et al. 2007; Faber et al. 2007). This quenching of star formation is apparently occurring in galaxies of increasingly lower masses as the Universe ages (Bundy et al. 2006). So-called ‘dry’ (gas-poor) mergers, with little associated star formation, can increase individual galaxy masses within the red sequence, forming the massive ellipticals seen today (van Dokkum 2005; Bell et al. 2006). As well as allowing the building of very massive ellipticals, such a scenario matches the observed kinematic and photometric properties of present-day ellipticals (Naab, Khocharf & Burkert 2006; Naab et al. 2007).

The overall decrease in global star formation rate (SFR) density since z ~ 1 appears to be caused by a gradual decline in the mean SFR of galaxies, rather than a decrease in the number of

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starbursts (Hammer et al. 1997; Noeske et al. 2007; Tresse et al. 2007). However, the process, or processes, responsible for this gradual decline remains to be determined. What physical mechanisms cause a galaxy to stop forming stars, to turn into a spheroid and thus to enter the red sequence? There are many competing theories which address one or both of these problems. Hot gas stripping (sometimes called strangulation) of small galaxies as they fall into overdense environments leads to a slow quenching of their star formation (Larson, Tinsley & Caldwell 1980; Balogh & Morris 2000; van den Bosch et al. 2008). In regions of high external pressure, the cold gas may also be stripped from the galaxies by ram pressure stripping (Gunn & Gott 1972; Cayatte et al. 1994). Gas-rich major mergers may perform both tasks, causing a starburst that is strong enough to rapidly exhaust the supply of fuel, and convert the disc galaxies into spheroids (Toomre & Toomre 1972; Barnes & Hernquist 1992; Naab & Burkert 2003). In this latter scenario, subsequent cooling from the intergalactic medium may cause a disc to reform and return the galaxy to the blue sequence. Therefore, the existence and efficient coupling to the interstellar medium (ISM) of additional mechanical energy from a central active nucleus [often called active galactic nuclei (AGN) feedback] have been proposed to prevent refuelling and allow the red sequence to build (Springel, Di Matteo & Hernquist 2005a; Hopkins et al. 2007; Khalatyan et al. 2008). Observational evidence for the existence, but above all the relative importance of each of these scenarios, remains scarce.

Much progress has been made on understanding galaxy mergers since the advent of high-resolution computer simulations. Realistic observational comparisons are now becoming easier through the application of observational filter functions, point-spread functions and radiative transfer of starlight through dust, to simulation outputs (e.g. Lotz et al. 2008). However, many areas of parameter space remain relatively unexplored with potentially large implications for our overall understanding of galaxy formation. For example, the comparison between simulations of galaxy mergers with and without mechanical AGN feedback is rarely focused upon, with some groups preferring to focus on starburst feedback and others on the possible impact of an active nucleus (for an exception, see Khalatyan et al. 2008).

In this paper, we compare observational results directly with a suite of smoothed particle hydrodynamic (SPH) simulations of galaxy mergers from Johansson, Naab & Burkert (2009, hereafter JNB09), both with and without AGN feedback, by converting the star formation histories of the simulated galaxies into integrated spectra, upon which the same analysis can be performed as upon the observations. Rest-frame optical spectra contain a wealth of information about a galaxy’s past and present star formation rate, often referred to as the galaxy ‘fossil record’ (e.g. Panter, Heavens & Jimenez 2003). In particular, the 4000 Å break and Hβ absorption line strengths constrain the specific star formation rate and amplitude of recent bursts of star formation (Kauffmann et al. 2003a).

At low redshift, the quality of spectra and models now allow the analysis of large spectral regions (Cid Fernandes et al. 2005; Tojeiro et al. 2007; Wild et al. 2007; Koleva et al. 2008). At high redshift, spectral indices easily separate blue from red-sequence galaxies without the complication of dust (Vergani et al. 2008). At these redshifts, where galaxy spectra are in general noisier, modern statistical techniques present us with the opportunity to vastly increase the quantity and improve the quality of derived parameters. Following Wild et al. (2007), this paper presents a principal component analysis (PCA) of the 4000 Å break region of more than 100 high-redshift galaxy spectra culled from the Visible Multi-Object Spectrograph (VIMOS) VLT Deep Survey (VVDS; Le Fèvre et al. 2005). We use the information encoded in the spectra to recover the recent star formation history of galaxies at an epoch when the Universe was very different from today.

From an observational perspective, so-called transition’ galaxies are of significant interest for pinning down which physical processes play the largest role in shaping the evolution of galaxies. Classes of galaxies which could be transitioning between the blue and red sequences are ‘post-starburst (PSB)’ galaxies (e.g. Tran et al. 2004; Quintero et al. 2004; Le Borgne et al. 2006; Kaviraj et al. 2007) and ‘green valley’ galaxies (e.g. Martin et al. 2007). From the buildup of the red sequence in the VVDS, Arnouts et al. (2007) measured the net mass flux which has taken place from the blue sequence to the red sequence. This amounts to $9.8 \times 10^{-3} \, M_\odot \, yr^{-1} \, Mpc^{-3}$ for a Chabrier (2003) initial mass function (IMF) or about $1.4 \times 10^3 \, M_\odot \, yr^{-1}$ in the entire VVDS survey volume. As we shall show in this paper, galaxies which have undergone sudden quenching of star formation can be identified in VVDS spectra for a period of $\sim 0.35$–$0.6$ Gyr after the quenching event. Therefore, if the entire buildup of the red sequence were due to a physical process associated with fast quenching, such as gas-rich major mergers, we could expect to identify a net transitioning stellar mass of $6 \times 10^{-2} \, M_\odot \, Mpc^{-3}$, or about $8.5$–$14 \times 10^{11} \, M_\odot$ in the VVDS survey, after accounting for targeting rates. This could comprise, for example, a few tens of galaxies of stellar mass log($M/M_\odot$) = 10.5.

The primary questions that we wish to address in this paper are, how much mass do we see entering the red sequence after an episode of fast quenching? Are gas-rich major mergers an important mechanism for the buildup of the red sequence since $z \sim 1$? Section 2 describes the VVDS spectroscopic survey and Section 3 presents our method for identifying PSB galaxies. In Section 4, we place our empirical results within a theoretical framework, through comparisons with simple synthesized stellar populations and the star formation histories of galaxy merger simulations. The results are presented in Section 5 and compared to the low-redshift Universe in Section 6. In Section 7, we discuss the global importance of PSB galaxies for developing a complete picture of the evolution of the galaxy population.

Throughout the paper, we assume a cosmology with $H_0 = 70 \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1}$, $\Omega_m = 0.3$ and $\Omega_{\Lambda} = 0.7$.

2 THE VVDS DATA SET

The VVDS is a deep spectroscopic redshift survey, targeting objects with apparent magnitudes in the range of $17.5 \leq I_{AB} \leq 24$. The survey is unique for high-redshift galaxy surveys in having applied no further colour cuts to minimize contamination from stars, yielding a particularly simple selection function. In this work, we make use of ~9000 spectra from the publicly available first epoch public data release of the VVDS-0226-04 (VVDS-02h) field which covers an area of 1750 arcmin$^2$ (Le Fèvre et al. 2005). The spectra have a resolution ($R$) of 227 and a dispersion of 7.14 Å pixel$^{-1}$ and a useful observed frame wavelength range, for our purposes, of 5500–8500 Å.

The first epoch public data release contains 8981 spectroscopically observed objects in the VVDS-02h field, 8893 of which are within the presently defined survey mask. Of these, 7194 have secure redshifts (flags 2, 3, 4 and 9; see below), are not classified as type 1 AGN and are not secondary objects in the slit. To measure each galaxy’s star formation history, we require coverage of the rest-frame wavelength range 3750–4140 Å, which restricts the redshift range of our galaxy sample to $0.5 < z < 1.0$. As discussed
in detail in Section 2.1.3, we impose a signal-to-noise (SNR) limit on the spectra greater than 6.5 and magnitude limits of 19 < \text{I}_{AB} < 23, resulting in a final sample of 1246 galaxies.

In addition to the spectra, the data set includes multiwavelength photometry from diverse sources. Data assembled within the context of the VVDS survey include deep B, V, R and I photometry from the Canada–France–Hawaii Telescope (CFHT)/CFHT12K camera\(^1\) with limiting magnitudes of 26.5, 26.2, 25.9 and 25.0, respectively (McCracken et al. 2003; Le Fèvre et al. 2004). Further optical photometry from the Canada–France–Hawaii Telescope Legacy Survey (CFHTLS\(^2\)) extends into the \(r\) and \(z\) bands. The field has deep near-infrared (NIR) imaging down to limits of \(J \approx 21.50\) and \(K \approx 20.75\) (Iovino et al. 2005) and near-ultraviolet (NUV) and far-ultraviolet (FUV) coverage as part of the \textit{GALEX} (Galaxy Evolution Explorer) mission (Martin et al. 2005). In order to avoid source confusion due to the large point spread function of \textit{GALEX}, ultraviolet (UV) photometry is based upon optical priors (Arnouts et al., in preparation). Infrared (IR) photometry in the Infrared Array Camera (IRAC) 3.6, 4.5, 5.8 and 8.0 \(\mu\)m is available from the Spitzer Wide-area Infrared Extragalactic survey (SWIRE; Lonsdale et al. 2003). We use the source catalogue as released by the SWIRE team,\(^3\) with detection limits at 5\(\sigma\) of 5.0, 9.0, 43.0, 40.0 \(\mu\)Jy, respectively. In this paper, the photometric data are used primarily for the purpose of deriving stellar masses, as described in Walcher et al. (2008, see Section 2.2).

2.1 Accounting for unobserved galaxies

In order to calculate absolute quantities from galaxy redshift surveys, such as galaxy numbers and mass densities, it is necessary to account for several effects which cause galaxies not to be included. For our work there are three effects.

(i) The \textit{target sampling rate} (TSR): only a fraction of all galaxies in the given magnitude range and survey area are targeted for spectroscopic followup.

(ii) The \textit{spectroscopic success rate} (SSR): a fraction of targeted and observed galaxies cannot be successfully assigned redshifts, due to either skyline contamination or featureless spectra.

(iii) The \textit{spectroscopic quality success rate} (QSR): only a fraction of the targeted galaxies with successful redshifts have high enough quality spectra from which star formation histories can be measured.

The TSR and SSR are common to many results derived from the VVDS, such as luminosity functions, and are explained in detail in, for example, Ilbert et al. (2005); only the QSR is new to this work.

2.1.1 The target sampling rate

As described in Ilbert et al. (2005), in order to maximize the number of targeted objects per VIMOS pointing, the TSR is a function of the size of the galaxy. We obtain the TSR from fig. 1 of Ilbert et al. (2005) and weight each galaxy according to its size \(w^{\text{TSR}}_{\text{spec}} = 1/\text{TSR} (r_i)\), where \(r_i\) is the \(x\)-radius parameter of each galaxy.

2.1.2 The spectroscopic success rate

The second effect, the SSR, is potentially much more complicated, because the success of obtaining a redshift for a galaxy depends not only on the apparent magnitude of the galaxy but also on its redshift and spectral type. The rest-frame spectroscopic features which allow accurate redshift determinations depend on the spectral type of the galaxy and move through the observed frame wavelength range depending on the redshift of the galaxy. In the VVDS, each object is assigned a redshift quality flag, which approximates the security of the given redshift. Galaxies with flags 2, 3, 4 and 9 are deemed secure.\(^4\) In order to account for the changing SSR as a function of redshift, and following the method presented in section 3.2 of Ilbert et al. (2005), we estimate the SSR by making use of the photometric redshifts calculated by Ilbert et al. (2006), which are publicly available through the Terapix Consortium.\(^5\) We calculate the SSR as a function of redshift and magnitude, as the number of objects with secure redshifts (flags 2, 3, 4, 9) divided by the total number of objects (with flags 0, 1, 2, 3, 4 and 9). Photometric redshifts are used to place the galaxies without secure spectroscopic redshifts in the correct redshift bin.

We calculate the SSR in four bins of apparent magnitude 19–21, 21–22, 22–22.5 and 22.5–23, with bins in \(\Delta \text{z}_{\text{phot}}\) of width 0.05. Galaxies brighter than 19 and fainter than 23 mag are not used in this work, the former because of our lower redshift limit of \(z = 0.5\) and the latter because of the signal-to-noise limitation we place on the spectra as described in the following section.

We weight each galaxy in our sample by \(w^{\text{SSR}}_{\text{spec}} = 1/\text{SSR}(z_{\text{spec}}, \text{I}_{AB})\), where \(z_{\text{spec}}\) is the spectroscopic redshift of the galaxy and \(\text{I}_{AB}\) is its \(I\)-band apparent magnitude.

It is important that galaxies with different SEDs are treated equally during this weighting procedure. Quiescent galaxies are the hardest to assign redshifts to, due to their lack of emission lines. To check that the completeness for quiescent galaxies is accurately estimated using the SED-independent method described above, we split our sample into high- and low-SFR subsamples, where SFR was measured from SED-fitting to multiwavelength photometry (see Section 2.2). We repeated the calculation of \(w^{\text{SSR}}_{\text{spec}}\) for each sub-sample and found them to be consistent with each other over the redshift range \(0.5 < z < 1\) used in this paper. This redshift range is expected to be the least problematic, due to the coverage of the 4000 Å break which is strong in quiescent populations.

2.1.3 The quality success rate

The final selection criterion applied to the VVDS galaxies to create the sample studied in this paper is that they have spectra of high enough continuum SNR to allow us to extract useful information on their star formation histories. In practice, this means a median per-pixel-SNR\(^6\) larger than 6.5. The SNR of the observed spectrum depends on both the apparent magnitude of the galaxy, because all galaxies are observed with equal exposure times, and the redshift of the galaxy, because the flux of a galaxy varies with wavelength. Thus, in a similar manner as for the SSR, we define the QSR to be the total number of galaxies with secure redshifts and SNR greater than our limit, divided by the total number of galaxies with secure redshifts (flags 2, 3, 4 and 9). We calculate this in the same four bins of apparent magnitude used for the SSR and in spectroscopic

\(^1\)http://cencosw.oamp.fr/
\(^2\)http://www.cfht.hawaii.edu/Science/CFHTLS
\(^3\)http://swire.ipac.caltech.edu/swire/swire.html
\(^4\)Flag 9: redshift determined from single emission line, flag 4: 100 per cent confidence, flag 3: 95 per cent confidence, flag 2: 75 per cent confidence (Ilbert et al. 2005).
\(^5\)ftp://ftpix.iap.fr/pub/CFHTLS-zphot-v1/
\(^6\)Per-pixel SNR is calculated from the median flux over error in the wavelength range 5500–8500 Å.
redshift bins of width $\Delta z = 0.05$. We weight each galaxy in our sample by $w_\text{QSR}^{\text{spec}} = 1/QSR(\ztext{spec}, I_{AB})$. The $w_\text{QSR}^{\text{spec}}$ is shown in Fig. 1 for the four magnitude bins. In Section 5.2, we will show that we recover stellar mass densities consistent with previous work, despite the addition of this new selection criterion.

Imposing a SNR threshold on the data was found to be necessary for this work. Using spectra with too low SNR causes considerable scatter in our spectroscopic indices, which makes difficult the robust identification of the PSB galaxies in which we are primarily interested. This problem is easily identifiable: the increased scatter in the indices causes the number of PSB galaxies to increase relative to the total sample and biases the SNR distribution of the candidate PSBs towards lower values than typically seen in the population as a whole. Therefore the SNR limit was chosen empirically, by ensuring that the distribution of SNR in our PSB galaxy sample was similar to that for galaxies of other types and that our completeness-corrected stellar mass densities for each class of galaxy (i.e., quiescent, star forming, PSB, starburst) remained constant when the SNR limit was increased by a small amount. We found that a per-pixel-SNR limit of 6.5 was required for the purposes of our study.

2.2 Measuring stellar masses

A full description of the method used to measure the stellar masses of our galaxies is given in Walcher et al. (2008; hereafter W08), to which we refer the reader for details. Briefly, we derive the stellar mass $M_\star$ for each galaxy by fitting its multiband UV–IR spectral energy distribution (SED), to model stellar populations created using the (Bruzual & Charlot 2003) population synthesis models, assuming a Chabrier (2003) IMF. We create a library of exponentially declining star formation histories with superposed stochastic top-hat bursts (see Kauffmann et al. 2003 and Salim et al. 2005 for descriptions of similar libraries). The method uses Bayesian probability distribution functions as described in appendix A of Kauffmann et al. (2003) to derive physical parameter estimates for each observed SED, including errors on the parameters. For a detailed discussion of the accuracy of stellar mass estimates using SED fitting methods, see Pozzetti et al. (2007).

2.3 Volume correction

To account for the changing effective survey volume for galaxies of different brightnesses and SED shapes, we use the $V_{\text{max}}$ method (Schmidt 1968). This weights galaxies according to the fraction of the survey volume in which they could have been observed, given their brightness and the shape of their SED. The latter point is important: galaxies with different SED shapes are visible in different survey volumes and this must be correctly accounted for in the $V_{\text{max}}$ calculation (Ilbert et al. 2004). Using the same library of models as used in the stellar mass determination (see above), the best-fitting model was scaled to the observed galaxy magnitude and shifted in redshift to determine the total redshift path in which the galaxy would have been seen, given the survey magnitude limits.

The SNR limit alters slightly the effective $I_{AB}$ magnitude limits of the survey, because very few galaxies with apparent magnitudes above 23 have spectra with a SNR greater than our limit of 6.5. We therefore redefine the survey magnitude range to be $19 < I_{AB} < 23$ and remove galaxies from our sample which fall outside of these limits.

2.4 The survey volume

The survey area is calculated from the photometric survey mask, combined with the boundaries of the spectroscopic survey region. The total survey area is 0.472 deg$^2$ which corresponds to a survey volume in the redshift range $0.5 < z < 1.0$ of $1.4 \times 10^6$ Mpc$^3$.

3 LOCATING RECENTLY DEAD GALAXIES

The galaxies in which we are interested are those in which a dominant A/F star population is visible, implying that the formation of O- and early B-type stars has ceased suddenly. Such galaxies are identifiable by their strong Balmer absorption lines compared to their mean stellar age as measured by their 4000 Å break strength. The traditional method for identifying PSB galaxies involves the selection of objects with both a strong Balmer absorption line (usually H$\beta$ or H$\delta$) to identify a recent starburst and no detectable nebular emission (usually [O I] or H$_{\alpha}$, although see Balogh & Morris 2000) to ensure no ongoing star formation. Our selection differs primarily by not placing limits on nebular emission, as we do not want to bias our sample against narrow-line AGN which are enhanced in the PSB population (Yan et al. 2006; Wild et al. 2007; Schawinski et al. 2007). The additional use of the 4000 Å break strength allows us to select galaxies with older and weaker PSB features.

Following the method of Wild et al. (2007), we employ a PCA of the spectra around the 4000 Å break to measure the strength of the Balmer lines with sufficient SNR. In Wild et al. (2007), the new spectral indices were defined based upon stellar population synthesis models to avoid contamination of the indices by gaseous emission from the galaxies. Because of the low spectral resolution of the VVDS spectra, in this work we are unable to accurately mask the Balmer emission lines which fall in the centre of the Balmer absorption lines in which we are interested. Therefore, we choose to perform the PCA directly on the VVDS spectra themselves. In Section 4, we explain how we compare a posteriori to model stellar populations created with a population synthesis code.

3.1 Calculating the spectroscopic indices

All galaxy spectra in our sample are corrected for Galactic extinction assuming a uniform $E(B-V) = 0.027$ (McCracken et al. 2003), moved to the galaxy rest frame and interpolated on to a common wavelength grid. Each spectrum is normalized, by dividing by the median flux between 3750 and 4140 Å. The mean spectrum is calculated and subtracted, and a PCA is then performed on the residuals. Because PCA is a least-squares process, eigenspectra calculated directly from data can easily be dominated by outliers in the input sample of spectra. In order to obtain robust eigenspectra that are representative of the majority of the population, we use an iterative and
We calculate the principal component amplitudes (PC) of all galaxies in our sample by projecting the spectra onto the eigenspectra. The projection is performed using the ‘gappy-PCA’ procedure of Connolly & Szalay (1999), which weights pixels by their errors during the projection, and gaps in the spectra due to bad pixels are given zero weight. We additionally allow the normalization of the spectra to vary as a free parameter in the projection (Lemson, private communication; see Wild et al. 2007). The PCs represent the amount of each eigenspectrum present in a galaxy spectrum and are our new star formation history indices. Errors are calculated during the projection of the spectra on to the eigenspectra, using the error arrays of the individual VVDS spectra. These errors are purely statistical, however, in Wild et al. (2007) we show that for SDSS spectra they compare well to the scatter observed between duplicate observations.

3.2 Defining the post-starburst galaxy sample

In Fig. 3, we show the distribution of PC1 and PC2 for our sample of VVDS galaxies. To guide the eye of the reader, and to aid in further discussion, we have split the sample into four ‘classes’, with boundaries empirically defined from the distribution of points. We would like to emphasize that in reality the star formation histories of galaxies form a continuous distribution, and any separation into discrete classes is an over simplification, greatly reducing the information contained within the full distribution. The primary division of our sample is into ‘quiescent’ and ‘star-forming’ galaxies on the right- and left-hand panels, based on the value of PC1 (i.e. the strength of their 4000 \(\AA\) break). The precise positioning of the boundary is arbitrary, and care should be taken when comparing our results for ‘red’ and ‘blue’ galaxies to those derived from different observations. To the bottom left, systems with very blue continua and very strong emission lines are found, which we class as ‘star-burst’ galaxies.

Finally, to the top centre we find the ‘PSB’ galaxies, with stronger Balmer absorption lines than expected for their 4000 \(\AA\) break strength. We define ‘PSB’ galaxies to have \(-0.6 < \text{PC1} < 1.0\) and \(\text{PC2} > 0.6\). While these boundaries were defined empirically from the distribution of data (this class is clear outliers in PC2), we will later compare with model stellar populations to justify their classification as ‘PSB’. We find that 18 galaxies lie in this region at > 1σ confidence. The spectra of these galaxies are shown in Fig. 4. The selection of these 18 galaxies is robust to changes in the exact method used to create the eigenspectra.
Figure 4. The spectra of PSB galaxies culled from the VVDS galaxy sample in the rest wavelength range 3750–4140 Å. Overplotted in red are the PCA fits to the spectra using 10 components.

3.3 Estimating completeness limits

It is important to estimate the completeness of the survey in terms of galaxy stellar mass. This of course depends upon the mass-to-light ratio and SED shape of the galaxies in question: flux-limited surveys are generally complete to lower mass limits for star-forming galaxies than for quiescent galaxies. While the completeness in a particular photometric band can be judged empirically, this is not possible for the completeness in derived parameters, such as stellar mass and star formation rate. We therefore use an alternative approach to estimate the mass completeness of our sample, described in detail in W08.

Because we are primarily interested in the PSB population, with mass-to-light ratios between those of star-forming and quiescent galaxies, we derive the mass limits relevant for this population alone. From the model data set described in Section 2.2, we select all model galaxies which have undergone a starburst in the last Gyr and lie within our PSB region in PC1/PC2. For a given stellar mass, we determine the fraction of model PSB galaxies that lie within our survey magnitude limits. We find that 50 per cent of the model PSB galaxies at $z = 0.6$ with $\log (M/M_\odot) > 9.5$ would be detected, and $\log (M/M_\odot) > 9.9$ at $z = 0.9$. The stochastic model library assumed in this analysis has a higher fraction of strong PSB galaxies than appear in the real data, i.e. while the observational PC1/PC2 space is fully covered by the models, the relative space density of the different galaxy types is not reliable. We therefore confirmed that the mass completeness limits did not vary greatly with burst mass fraction or burst age.

In the following sections, all results will be quoted for a mass limit of $\log (M/M_\odot) > 9.75$. We have confirmed that increasing this limit to $\log (M/M_\odot) > 10.0$ does not alter our conclusions. Fig. 3 (right) shows the number density of galaxies in bins of PC1/2 for galaxies with $\log (M/M_\odot) > 9.75$, corrected for survey volume and sampling effects.

4 COMPARISON WITH MODELS

In order to understand the particular properties of a starburst which would lead to a PSB galaxy in our sample, and to measure the time-scale during which a PSB galaxy is visible, it is necessary to compare our data with model stellar populations. We begin by creating simple toy model starbursts and subsequently turn to the analysis of SPH simulations of merging galaxies.

4.1 Toy model galaxy tracks

For a galaxy to reveal strong Balmer absorption lines, star formation must switch off rapidly resulting in an excess of longer lived A and F stars over the hotter O and early B stars. This does not necessarily have to be preceded by a short-lived starburst, the sudden truncation of ordinary star formation will suffice, although the signature will of course be weaker. The two parameters of importance for the strength and longevity of the PSB phase are the mass fraction of stars formed during the starburst and the decay time-scale of the starburst. In this terminology, a truncation model then simply has a mass fraction of zero per cent.

With this in mind, we have created a library of model galaxies which undergo exponentially decaying bursts, occurring after 5 Gyr of continuous star formation. These bursts are parametrized by their decay time and burst mass fraction, i.e. the mass of stars formed while the star formation rate is above the continuum level.

Converting the star formation histories into spectra suitable for comparison with the VVDS data set requires several steps. We input the star formation histories into the GALAXEY code (Bruzual & Charlot 2003), using Charlot & Bruzual (in preparation) simple stellar populations (SSPs), a Chabrier (2003) IMF and assuming solar metallicity. The evolution of the model galaxies in PC1/2 is not greatly affected by the change between Bruzual & Charlot (2003) and Charlot & Bruzual (in preparation) SSPs, which involves...
a change both in stellar libraries and in the stellar evolution tracks. Solar metallicity was chosen as being suitable for our PSB galaxy sample, given their stellar masses (Section 5.1), but the evolutionary tracks are insensitive to moderate variations in metallicity. The two-component dust prescription of Charlot & Fall (2000) is applied to the continuum light as implemented in the GALAXEV code. Again, the inclusion of or not of continuum dust has little effect on the time spent on the PSB sequence, or the maximum PC2 observed. This is because the dominant A/F star population in the PSB spectra is assumed to already have emerged from the dense stellar birth clouds.

Next, because the resolution of the VVDS spectra is too low to mask emission lines in the data, we must add emission lines to the model spectra. We convert the rate of ionizing photons predicted by the stellar population synthesis model (Q_{ion}) into Hα line flux using

$$F_{Hα}(\text{erg s}^{-1}) = 0.45 E_{Hα}(\text{erg}) Q_{ion}(\text{s}^{-1})$$

where $E_{Hα}$ is the energy of a Hα photon and 0.45 is the fraction of ionizations which lead to the emission of an Hα recombination photon (case B, $T_e = 1 \times 10^4$ K and $N_e = 1 \times 10^4$ cm$^{-3}$; Storey & Hummer 1995). The remaining Balmer line fluxes are derived from the ratios given in Osterbrock (1989). The stellar population synthesis model includes the post-AGB phase of stellar evolution which is believed to be important for producing ionizing photons in older stellar populations (Binette et al. 1994). We note that no contribution to the emission lines from obscured, narrow-line AGN is included in the models. Any substantial infilling of the Balmer absorption lines in this way will prevent us from identifying PSB galaxies. AGN with strong enough lines to have a significant effect are extremely rare however, and their absence from our sample will not affect our final results.

Just as dust attenuation is applied to the model stellar continua, the lines are similarly attenuated using the attenuation law as described in Wild et al. (2007):

$$\frac{\tau_λ}{\tau_V} = (1 - \mu) \left(\frac{λ}{5500 \, \text{Å}}\right)^{-1.3} + \mu \left(\frac{λ}{5500 \, \text{Å}}\right)^{-0.7}.$$  

This law is inspired by the two-component dust model of Charlot & Fall (2000). For the birth clouds, from which nebular emission is believed to originate and which contain a fraction $1 - \mu$ of the dust, these authors adopted for simplicity an attenuation law to match that of the diffused ISM (i.e. of the form $λ^{-0.7}$). Our slightly steeper curve, resulting in slightly increased attenuation, is motivated by the fact that dense clouds around young stars have a more shell-like geometry than the diffused ISM (see da Cunha, Charlot & Elbaz 2008 for more details). The attenuation of the model emission lines by a moderate amount ($A_V = 1.0$) alters slightly the evolutionary tracks in PC1/PC2 of the model during the starburst phase.

Our ability to detect a PSB galaxy depends on the maximum PC2 reached during the evolution of the stellar population and the time spent in the PSB phase ($t_{PSB}$). These factors depend in turn on the strength of the proceeding starburst, together with the time-scale of the subsequent decay of the star formation rate ($τ_{decay}$). Fig. 3 shows that the maximum PC2 reached by the VVDS galaxies is around 1.0, with $t_{PSB} > 0.9$. Using our toy models, the left-hand panel of Fig. 5 shows the maximum value of PC2 attained by a model galaxy after the burst has occurred, as a function of the burst mass and burst decay time. The models show that the descendants of starbursts with decay times $τ_{decay} \lesssim 0.1$ Gyr and burst fractions above a few per cent will appear clearly in the PSB phase. The right-hand panel of Fig. 5 shows the time spent in the PSB phase ($t_{PSB}$). This time is short, $τ_{PSB} \lesssim 0.15$ Gyr, for burst mass fractions <5 per cent, and reaches a maximum independent of decay time of $≈0.6$ Gyr for mass fractions of $>30$ per cent. We will use this value as an upper limit on $t_{PSB}$ in later sections.

We conclude from this section that the majority of the progenitors of our PSB galaxies underwent a recent strong starburst, followed by a rapid truncation of the star formation. A small fraction may, however, be simply the result of rapid truncation of their ongoing star formation.

### 4.2 Simulation galaxy tracks

The next step in our comparison with models involves a sample of 79 merger simulations presented in JNB09.

#### 4.2.1 Simulation details

The simulations were performed using the entropy conserving TREEBH code GADGET-2 (Springel 2005), which includes radiative cooling for a primordial mixture of hydrogen and helium together with a spatially uniform time-independent local UV background. Star formation and the associated supernova feedback are implemented using the subresolution multiphase model developed by Springel & Hernquist (2003). We model the feedback from black holes (BHs) following the effective subresolution model of Springel, Di Matteo & Hernquist (2005b), in which the unresolved

Figure 5. By projecting evolving model stellar populations on to the VVDS eigenspectra, we can measure quantitative properties relevant to our PSB galaxies. After continuously forming stars for 5 Gyr, the toy-model galaxies undergo a starburst which declines exponentially with decay time $τ_{decay}$. Left-hand panel: the maximum PC2 attained by the models after the starburst has occurred, i.e. a measure of the strength of the PSB features. Different lines represent models with bursts of different $τ_{decay}$. Right-hand panel: the time spent in the PSB phase as a function of burst mass fraction.
accretion on to the BH is related to the resolved gas distribution using a Bondi–Hoyle–Lyttleton parametrization (Bondi & Hoyle 1944). Further details concerning the feedback implementations and parameter choices can be found in JNB09. In addition, for the purposes of this paper a new suite of simulations was performed in which the BH feedback was switched off. Such a comparison is important because the BH feedback can cause star formation to completely shut down after the merger, which may plausibly affect both the time the merger remnant spends in the PSB phase and the strength of the PSB features.

The simulations include mergers of gas-rich discs (Sp–Sp), of early-type galaxies and discs (E–Sp, mixed mergers), and mergers of early-type galaxies (E–E, dry mergers). The progenitor galaxies have a range of virial velocities, $v_{\text{vir}}$, of 80, 160, 320 and 500 km s$^{-1}$, which determines their masses and sizes (see equations 1 and 2 in JNB09). All model galaxies contain an exponential disc ($d$) component, together with a stellar bulge ($b$) embedded in a dark matter halo modelled with the Hernquist (1990) profile. The stellar bulge has a fixed mass ratio of $M_{b}^d = 0.01367 M_{\odot} = 1/3 M_{\text{tot}}$, where the total disc mass is a sum of the disc stellar and gas mass $M_{d,\text{tot}} = M_{d}^{s} + M_{d,\text{gas}} = 0.041 M_{\odot}$, the disc stellar mass is $M_{d}^{s} = 0.041 (1 - f_{\text{gas}}) M_{\odot}$, and $M_{\odot}$ is the virial mass of the galaxy. The initial gas fraction $f_{\text{gas}}$ takes values of 0.2, 0.4 and 0.8. The galaxies approach each other on parabolic orbits, which are generally motivated by statistics from $N$-body simulations (Khochfar & Burkert 2006). The resulting merger remnants have total stellar masses between log($M/M_{\odot}$) = 9.5 and 12.5. Both major (1:1) and minor (3:1) mergers were simulated with varying orbital and initial disc geometries (Naab & Burkert 2003). All simulations were evolved for a total of $t = 3$ Gyr, with the merger taking place after approximately 1.5 Gyr, using the local Altix 3700 Bx2 machine hosted at the University Observatory in Munich. In this paper, we will primarily concentrate on mergers with prograde in-plane orbits (‘G0’), i.e. the galaxies collide directly edge-on; Naab & Burkert 2003). We will additionally show an example in which galaxies rotate in a retrograde sense, with the discs tilted by 30 deg with respect to one another (‘G7’).

We will focus exclusively on the Sp–Sp mergers, as all other pair combinations were found not to produce the strength of PSB galaxy visible to us in the data.

As the simulations, and thus star formation rates, are only computed over a total duration of 3 Gyr, we must assume a star formation history and galaxy age for the initial buildup of stellar mass in each progenitor galaxy. We assume that by the start of the simulation each galaxy has built both its bulge and disc stellar mass through an exponentially declining star formation rate: $\text{SFR} = \text{SFR}_{0} + n \exp(-t/\tau)$ where $\tau = 1$ Gyr. $\text{SFR}_{0}$ is the initial SFR of the simulation i.e. $\sim 1.5$ Gyr before the merger takes place. $n$ is defined such that the galaxies are 5 Gyr old at the start of the simulation, i.e. the stellar populations are approximately 7.5 Gyr old at the onset of the merger. Both progenitors in a simulation are assumed to undergo the same initial SFH. We note that any similar star formation history can be assumed with which to build the pre-merger galaxies, without significantly affecting their evolution in the post-merger PSB phase. The creation of the spectra from the SFHs of the simulations follows exactly the same method as for the toy burst models.

### 4.2.2 Post-starburst galaxies in merger simulations

Fig. 6 shows the star formation history and evolutionary tracks in PC1/2 for three of the major merger simulations with $f_{\text{gas}} = 0.2$ (left-hand pair of panels) and 0.4 (right-hand pair of panels), BH feedback and prograde, edge-on orbits (‘G0’) over the 3 Gyr of the simulation. From top to bottom panel, the mass of the progenitor galaxies increases. The SFHs of the major merger simulations in general follow similar patterns, with an initial weak enhancement in their star formation, quickly followed by the starburst and decay to zero star formation.

We parametrize the simulations using two simple values to describe the evolution of the starburst. First, the burst mass fraction $f_{\text{burst}}$, defined as the mass of stars formed while the SFR is at least 1.05 times the continuum rate, divided by the total mass of the final merger remnant. The continuum rate is measured in the first

![Figure 6](https://example.com/figure6.png)

**Figure 6.** Left panel: the combined star formation history of both galaxies participating in a major merger during the 3 Gyr SPH simulation. In these panels, the galaxies collide in a ‘G0’ orbital configuration and BH feedback is included. Progenitor galaxies have gas fractions of 20 per cent and virial velocities of 80 (top), 160 (middle) and 320 (lower) km s$^{-1}$ corresponding to stellar masses of around $10^{10}$, $10^{11}$ and $10^{12} M_{\odot}$. The red part of the SFH depicts the ‘starburst’ phase, defined to be where the SFR is 5 per cent greater than the continuum SFR. The values in the top left of the panels are the mass fraction of stars formed during the starburst and the decay time-scale of the starburst (see the text). Next left panel: the corresponding evolutionary tracks in PC1/PC2, with the red section corresponding to the red section in the left-hand panel. The dotted box shows the PSB region defined in this paper. The time that the merged galaxy spends in the PSB phase is given in the bottom left of the panels. Right pair of panels: Same as the left pair of panels, but for progenitor galaxies with gas fractions of 40 per cent.
Figure 7. Same as for Fig. 6 but for different initial conditions. Left pair of panels: simulations in which the progenitor galaxies collide with inclinations other than edge-on. From top to bottom, the orbits are ‘G7’, ‘G10’ and ‘G13’. The galaxies have gas mass fractions of 20 per cent (compare to left-hand panels of Fig. 6). Right pair of panels: simulations in which the BH feedback has been switched off. The progenitor galaxies have gas mass fractions of 40 per cent (compare to right-hand panels of Fig. 6).

Gyr of the simulation, and linearly extrapolated across the subsequent starburst. The second parameter is the decay time of the starburst, $t_{\text{decay}}$, defined to be the time from the peak of the starburst until the SFR is only 10 per cent of the maximum burst height. These values are shown in the top left of each SFH panel in Fig. 6. As found using the toy models, higher gas fractions lead to stronger PSB features and longer periods of time spent in the PSB phase.

Using this suite of simulations, we can investigate several other initial conditions which affect the evolution of the stellar population of the merger remnant: progenitor mass ratio; orbital geometry; presence or absence of a BH. We illustrate the latter two in Fig. 7. The left two panels show the star formation history and evolutionary tracks in PC1/2 for galaxies with tilted orbital configurations and $f_{\text{gas}} = 0.2$. Comparing to the left panels of Fig. 6, we see that in this particular suite of simulations only the prograde edge-on mergers give rise to PSB features. While the starbursts are weaker in the other orbital configurations, it is likely that the main cause of the difference is in the longer decay times of the star formation rate. However, we caution that the tilted orbital geometries tested here have typical tilts of $\gtrsim 30^\circ$ and are retrograde. Other relevant parameters, such as impact parameter, galactic structure and variations in stellar feedback prescription have not been investigated. While the simulations indicate that a relatively strong interaction is required to produce a PSB galaxy (see also Cox et al. 2008; JNB09), a full study of the post-merger stellar populations as a function of impact geometries is beyond the scope of this paper.

The right two panels of Fig. 7 show the evolution of the stellar population with BH feedback ‘switched off’ and $f_{\text{gas}} = 0.4$. Comparing to the right-hand panels of Fig. 6, we see that the burst mass fractions and time spent in the PSB phase are similar with or without the presence of BH feedback. The primary causes of the shutdown in star formation are supernovae feedback and exhaustion of gas supplies, rather than any additional energy supplied by the AGN. In two out of three cases, the PSB features are stronger when BH feedback aids in expelling the gas, but the main effect is focused on the later stages of the burst where any residual star formation is halted more quickly. Therefore, we conclude that from these spectral indices alone, there is no way to confirm or refute the suggestion that strong BH feedback provides the mechanism for shutting off star formation in the Universe.

In Fig. 8, we summarize the results by showing the time spent in the PSB phase and maximum value of PC2 reached after the

Figure 8. Same as Fig. 5 except for SPH galaxy merger simulations with ‘GO’ orbits. Different shapes represent different gas fractions of the progenitor galaxies, filled symbols are 1:1 mass ratio mergers and open symbols are 3:1 mass ratio mergers. Increasing symbol size denotes increasing stellar mass. Grey symbols are mergers with BH feedback ‘switched-off’, 40 per cent gas fractions and $v_{\text{vir}} = 80$, 160 and 320 km s$^{-1}$. Left-hand panel: the maximum PC2 attained by the models after the starburst has occurred, as a function of burst mass fraction. The dotted line indicates our observational limit above which PSBs are detected. Right-hand panel: the time spent in the PSB phase.
merger has occurred, for all of the Sp–Sp merger simulations with prograde in-plane orbits (‘GO’, i.e. directly edge-on). The results paint a very similar picture to that shown by the toy models, but we can now associate burst mass fractions to physically meaningful parameters such as gas fractions and galaxy masses. We find that mergers must induce burst mass fractions of at least 5 per cent for them to be detectable in our observationally defined PSB phase, and the time spent there is greater for more gas-rich and more massive mergers. For a 3:1 merger (open symbols) to appear in the PSB phase, a very high gas fraction of 80 per cent is apparently required. The duration of the PSB phase tends to a maximum of 0.6 Gyr, with lower gas fractions leading to shorter time-scales of 0.3–0.4 Gyr and burst mass fractions of 5–10 per cent. Similar to the toy models, we find that decay times of the starburst must be shorter than ~0.3 Gyr for a PSB galaxy to be observed. The results of three simulations with BH feedback ‘switched off’, \( f_{\text{gas}} = 0.4 \) and a range of virial masses are shown as grey symbols. These can be compared directly to the filled triangles in the same figure, in which BH feedback has occurred. We note that the burst mass fractions and starburst decay time-scales derived in this section are the same as those found for luminous IR galaxies (LIRGs; Marcillac et al. 2006).

Many of the simulated galaxy mergers in the full library of 79 simulations do not result in a PSB remnant according to our demanding observational criteria. Even for gas-rich major mergers, the starbursts can occasionally be weak and/or have long decay times, thus not creating the sharp discontinuity in SFR required for them to appear in the PSB phase. Such galaxies may enter the red sequence through the ‘green valley’ if their star formation rate continues to decay.

### 5 MASS DENSITIES AND MASS FLUXES OF PSB GALAXIES AT Z ∼ 0.7

In the preceding sections, we have culled a sample of PSB galaxies with 0.5 < z < 1.0 from the VVDS redshift survey. Through comparisons with toy models and SPH galaxy merger simulations, we have shown how the spectroscopic features indicate that the galaxies have undergone a recent major, gas-rich merger. In this section, we will place the PSB galaxies into a global context, in terms of their stellar masses, star formation rates and their number and mass densities. Finally, we will address the interesting question: how much mass enters the red sequence through the PSB phase?

#### 5.1 Photometrically derived physical properties

We can now ask how the mass of the PSB galaxies compares to that of the blue- and red-sequence galaxies? Fig. 9 shows the mass distributions of our different classes of galaxies, before and after corrections for sample selection (TSR, QSR and SSR) and survey volume. The galaxies have been classified according to their spectral types i.e. position in PC1/PC2. For clarity, we have combined the starburst and star-forming galaxies into a single class; their mass distributions are very similar. The left-hand panel shows the mass distribution before correcting for completeness effects. The right-hand panel shows the completeness-corrected mass distribution, indicating that the PSB galaxies primarily have \( \log(M/M_\odot) < 10.5 \), i.e. to the lower end of galaxies in the red sequence and with a similar distribution to galaxies on the blue sequence. It is also worth noting that the completeness-corrected mass distribution of the PSB galaxies continues to rise to lower masses, and does not turn over before we reach the completeness limit of the sample.

![Figure 9](image_url)

**Figure 9.** The mass distribution of galaxies, classified into star-forming (blue), quiescent (red) and PSB (orange, dot-filled) by their spectral type i.e. their PC1/PC2 values shown in Fig. 3. The orange line-filled histograms indicate the subset of PSB galaxies with no ongoing residual star formation. The vertical dotted line indicates our PSB mass completeness limit. Left-hand panel: the raw data, with no correction for survey incompleteness effects. Right-hand panel: for galaxies with stellar masses above our completeness limit, after correction for survey incompleteness effects.

Deeper spectroscopic surveys will be required to fully probe the mass distribution of PSB galaxies.

Our spectroscopic analysis has focused on uncovering the special class of PSB galaxies, and not on recovering further physical parameters. As described in Section 2.2 and more fully in W08, the multiwavelength (UV–IR) SEDs of these galaxies have been analysed to obtain more physical properties than just stellar mass. In Fig. 10, we present the light-weighted mean stellar age, specific
star formation rate (SFR/$M^*$), time of last burst and dust content of our full sample of galaxies, classified by their PC1/PC2 values. Overall, the relative agreement between the SED fitting and VVDS spectral fitting is remarkable: galaxies which are spectroscopically classified as star forming are found, from multwavelength photometry, to be younger, have high star formation rates, more recent starbursts and higher dust contents compared to galaxies spectroscopically classified as quiescent. The multwavelength photometry is able to distinguish that the PSB galaxies have ages and star formation rates intermediate between the quiescent and star-forming galaxies. Additionally, the estimated time of their last starburst has a lower mean value than quiescent galaxies, peaking at $10^8$–$10^9$ yr, exactly as expected from the VVDS spectral analysis. We can see that the PSB galaxies, identified purely through their stellar continuum as having undergone a recent starburst, have a range of specific star formation rates which place them from the lower end of the star-forming sequence through to the quiescent galaxies. In Section 5.3, we will use this result to set a lower limit on the mass flux on to the red sequence through the PSB phase, by identifying those galaxies which have completely ceased star formation.

5.2 Mass and number density

Summing up all the galaxies in our sample above the mass completeness limit of log $M = 9.75$ with the appropriate weightings, we obtain a total stellar mass density of log $\rho^* = 8.23^{+0.03}_{-0.04}$. The errors account for individual errors on the stellar masses and Poisson errors from the SSR and QSR weights. As we have placed a stringent criterion on the minimum SNR of the spectra, it is important to ensure that we recover the correct total stellar mass density found in other work. Pozzetti et al. (2007) calculate the total mass density of galaxies as a function of redshift in the VVDS spectroscopic sample, using the same Chabrier (2003) IMF as used in this work. Integrating a Schechter function with the parameters given by Pozzetti et al. for the redshift range $0.7 < z < 0.9$ above our mass limit of 9.75 gives a stellar mass density of log $\rho^* = 8.28$. Although the statistical errors are always <10 per cent, Pozzetti et al. quote a typical scatter between different methods of mass determination and luminosity function estimates of at least ~0.1 dex. Taken together with the slightly different redshift range, our results appear to be entirely consistent with those of Pozzetti et al.

Table 1 gives the mass and number densities for each of our galaxy classes. Note that the completeness of our survey is lower for quiescent galaxies than for other classes.

Focusing on the PSB galaxies, we find a number density of $1.0 \times 10^{-4}$ Mpc$^{-3}$ and mass density of $2.69 \times 10^6 M_\odot$ Mpc$^{-3}$. It is instructive to compare their number density to other objects considered to be unusual in the Universe at these redshifts. The number density of our PSB sample is $0.3$–$0.5$ dex above the number density of powerful X-ray selected AGN with 2–8 KeV luminosities above $10^{43}$ erg s$^{-1}$ at redshifts $0.5 < z < 1.5$ (Barger et al. 2005). They are factor of 10 more numerous than star-forming galaxies at these redshifts with radio luminosities similar to local ultra luminous IR galaxies (ULIRGs; Cowie et al. 2004). The PSB galaxies are considerably more common than submillimetre selected galaxies with FIR luminosities $\geq 6 \times 10^{11} L_\odot$ at $z \approx 0.9$, which have number densities of $3 \times 10^{-6}$ Mpc$^{-3}$ per decade (Chapman et al. 2005). These comparisons are designed for orientation only, and not to imply evolutionary sequences: the very different duty cycles and ‘on’ times for different classes of rare objects make inferences about the relation between them difficult. We will return to a quantitative comparison with QSO number densities and major merger rates in Section 7.

5.3 The mass flux of post-starburst galaxies on to the red sequence

We are interested in how much mass may enter the red sequence after a starburst and subsequent fast quenching of the star formation as seen in simulations of major mergers. We estimate the total mass flux which passes through the PSB phase to be

$$\rho_{PSB} = \frac{1}{t_{PSB}} \sum_{i=1}^{N_{PSB}} M^*_i w_i V_{max,i},$$

where $M^*$ is the stellar mass of the galaxy in solar masses, $w$ is the combination of the selection functions $w^{SSR}$, $w^{PSR}$ and $w^{QSR}$ and $V_{max}$ is the correction for the volume in which each galaxy can be seen. The sum is over PSB galaxies above the mass completeness limit of log($M/M_\odot$) > 9.75. $t_{PSB}$ is the time a galaxy will be seen in the PSB phase. From Section 4, we find $t_{PSB}$ to be less than 0.6 Gyr. Galaxy mergers with lower gas fractions of around 20–40 per cent result in slightly smaller burst mass fractions and shorter time spent in the PSB phase of ~0.35 Gyr.

During the selection of our PSB galaxy sample, we have imposed no restrictions on nebular emission line strengths (see Section 3). However, galaxies which show PSB signatures as well as nebular emission lines may be in the process of regenerating their star formation and may therefore subsequently return to the blue sequence. In order to derive a firm lower limit on the mass flux entering the red sequence through the PSB phase, we elect to sum only those PSB galaxies which show no evidence of star formation. Inspecting the distribution of SSFRs of our PSB galaxies (top-right panel of Fig. 10) shows the majority have SSFRs similar to the lower end of the star-forming sequence, six objects have SSFRs below $10$–$11$ yr$^{-1}$, five of which lie above our mass completeness limit. We note that these galaxies also have no measurable [O II] emission. The mass distribution of these galaxies is indicated in Fig. 9 by the filled line histogram and their positions marked in PC1/2 by the open circles in Fig. 3.

Table 1. The mass and number densities of each of our classes of galaxies, for a mass limit of log ($M/M_\odot$) > 9.75.

| Class     | Quiescent | Star forming | Starburst | PSB | Total |
|-----------|-----------|--------------|-----------|-----|-------|
| log (number Mpc$^{-3}$) | $-2.5$   | $-2.9$   | $-3.1$   | $-4.0$ | $-2.3$   |
| log($\rho^*/M_\odot$ Mpc$^{-3}$) | $7.89^{+0.01}_{-0.01}$ | $7.88^{+0.02}_{-0.02}$ | $7.17^{+0.03}_{-0.04}$ | $6.43^{+0.06}_{-0.04}$ | $8.23^{+0.01}_{-0.01}$ |

7 We compare to the I-band selected sample with masses determined from complex star formation histories (row 7 of their table 2), for better comparison with our own sample and masses.
Summing equation (3) over the five PSB galaxies above the mass completeness limit with negligible ongoing star formation as derived from their SEDs, assuming an upper limit for $\Omega_{PSB}$ of 0.6 Gyr, results in a lower limit on the mass flux entering the red sequence through the PSB phase of $\dot{\rho}_{\text{PSB}} > 0.0022_{-0.0006}^{+0.0009} M_\odot \text{Mpc}^{-3} \text{yr}^{-1}$. Our best estimate for the mass flux through the PSB phase on to the red sequence, assuming $\Omega_{PSB} = 0.35\text{Gyr}$, is $\dot{\rho}_{\text{PSB}} = 0.0038_{-0.0004}^{+0.0006} M_\odot \text{Mpc}^{-3} \text{yr}^{-1}$. We note that this is still a lower limit, as we have excluded all those PSB galaxies with detectable levels of ongoing star formation. This residual star formation may still decay as the PSB ages, we note that the younger PSB galaxies (those with smaller PC1) are found to be more likely to have residual star formation than older PSB galaxies (see circled points in Fig. 3). If all the PSB galaxies were to enter the red sequence, for $\Omega_{PSB} = 0.35\text{Gyr}$ the mass flux would be $\dot{\rho}_{\text{PSB}} = 0.0077 M_\odot \text{Mpc}^{-3} \text{yr}^{-1}$.

To determine how important this mass flux is in terms of the global buildup of the red sequence, we compare to Arnouts et al. (2007). They use the multiband photometric data in the same VVDS-02h field to measure the mass buildup of the red sequence; comparison with this result thus limits our exposure to cosmic variance. The galaxy masses are measured using the same code and model data set as in this paper, thus eliminating one more potential source of systematic error. They find that 38% of the growth of the red sequence is $\dot{\rho}_{\text{PSB}} = 0.0098 M_\odot \text{Mpc}^{-3} \text{yr}^{-1}$. If we assume that all galaxies that enter the red sequence subsequently remain on the red sequence, then our results show that $>22.7_1^+2$ per cent and likely as much as $38_{-1}^{+2}$ per cent of the growth of the red sequence at $z < 1$ takes place from galaxies which have passed through the strong PSB phase. If all our PSB galaxies with $\log(M/M_\odot) > 9.75$ enter the red sequence, they account for $\sim80$ per cent of the growth of the red sequence. We note that these numbers are significant, and perhaps even surprisingly high. We will return to this point in Section 7.

The quoted errors on our mass flux include errors on the individual galaxy stellar masses, calculated from the probability distribution function resulting from the Bayesian SED fit, and the Poisson errors on the QSR and SSR weights. As described in Pozzetti et al. (2007), systematic errors caused by the methods used to estimate the masses and selection of samples lead to a typical scatter in stellar mass densities of 0.1–0.2 dex. If we discard our statistical errors, and assume instead a fixed 0.15 dex error on the stellar mass density of the PSB galaxies, we find $\dot{\rho}_{\text{PSB}} = 0.0038_{-0.0002}^{+0.0003} M_\odot \text{Mpc}^{-3} \text{yr}^{-1}$. However, our comparison with the results of Arnouts et al. (2007) should be more robust due to the use of the same stellar masses, similar survey selection criteria and survey area.

6 COMPARISON AT LOW REDSHIFT

To create a comparison sample at low redshift, we combine the SDSS spectroscopic data release 5 (DR5; Adelman-McCarthy et al. 2007) with the UKIRT (United Kingdom Infrared Telescope) Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007) large survey area (LAS), data release 3 (Warren et al. in preparation). The SDSS DR5 galaxy catalogue (Strauss et al. 2002) covers 5740 deg$^2$ and contains more than 670 000 spectra of galaxies with a median redshift of $z \sim 0.1$ and $r_{AB} < 17.77$. The accompanying SDSS photometric survey provides optical $ugriz$ photometry for each object. UKIDSS is an ongoing survey using the UKIRT Wide Field Camera (WFCam; Casali et al. 2007) to obtain $YJHK$ NIR photometry covering 4000 deg$^2$ in the same region of the sky as the SDSS survey. The photometric system is described in Hewett et al. (2006), the pipeline processing and science archive are described in Hambly et al. (2008). The LAS reaches a depth in $K$ of 18.4.

For the purposes of this paper, the SDSS provides the spectroscopic data required to locate the PSB galaxies, and the NIR photometry of the UKIDSS survey is combined with the optical photometry of SDSS to obtain accurate stellar masses. Requiring the objects to be detected in all $YJHK$ bands gives a combined survey area of 916 deg$^2$ (Maddox, private communication).

6.1 Sample selection and incompleteness corrections

We select SDSS galaxies to have extinction-corrected $r$-band petrochemical magnitudes $r_{AB} < 17.7$, be primary galaxy targets (PRIMTARGET = TARGET_GALAXY or TARGET_GALAXY_BIG or TARGET_GALAXY_RED), primary catalogue objects (mode = 1) and spectroscopically classified as a galaxy (SPECTCLASS = 2). They are matched to UKIDSS galaxies by identifying the closest object within 0.5 arcsec. We remove a small fraction of galaxies (3 per cent) with bad spectra by imposing a per-pixel-SNR limit of 5, and account for this loss in our weighting scheme. Our final sample contains 148 22 galaxies with $0.05 < z < 0.1$.

The redshift range is selected with two things in mind. First, we require low enough redshift that our sample is complete down to similar masses as for the VVDS survey and secondly we require high enough redshift to minimize the aperture bias effect caused by the 3 arcsec SDSS fibres. This latter property of the SDSS survey means that the spectra only probe the central regions of nearby, or massive, galaxies, with a strong redshift dependence. For our comparative census of PSB galaxies, this is problematic as there is currently no known way to robustly detect PSB features from optical photometry alone. Thus, it is not possible to know for sure whether the proceeding starburst was nuclear or global, the former being unlikely to be connected to the build-up of the red sequence. At $z = 0.05$, the fibre corresponds to a physical diameter of about 3 kpc ($h = 0.7$), which is small as compared to the size of a galaxy, but is considerably larger than the extent of a nuclear starburst (Börker et al. 2004). A remaining limitation caused by the aperture bias of SDSS is that PSB populations may fail to be identified due to population gradients within the galaxies. Assuming discs are more likely to undergo starbursts than bulges, this would cause us to underestimate the number of PSB galaxies.

Volume corrections and stellar masses of the galaxies are measured in the same way as for the VVDS sample (Section 2.3), using the combined UKIDSS and SDSS photometry. One final piece of information required is the TSR of SDSS. Although the SDSS aims for 100 per cent coverage in the spectroscopic catalogue, one of a pair of neighbouring galaxies is occasionally not targeted, due to the problem of placing fibres close together on a plate. Similarly, densely populated regions of the sky may suffer from partial coverage due to there being insufficient fibres available to cover the area.

For the purposes of this study, we only require the probability that a galaxy was targeted for spectroscopic followup, and no further spatial information. We use the SDSS Catalogue Archive Server (CAS) to count the number of galaxies within SDSS spectroscopic sectors that are targeted for spectroscopic followup and the number with spectroscopic ID numbers (i.e. that were targeted). We find that...
the targeting success rate is 90 per cent. We calculate weights for the galaxies by combining this value with the fraction with spectra above the SNR limit described above.

6.2 Calculating the principal components

To calculate the PCs for the SDSS spectra, we first correct for Galactic extinction, convert to air wavelengths, convolve the spectra to VVDS resolution and finally rebin on to the eigenspectra binning. We then proceed as for the VVDS spectra (Section 3.1), to obtain the PCs for the SDSS galaxies. The distribution of the first two components is shown in Fig. 11. The left-hand panel shows the full sample and the right-hand panel only galaxies with log(M/M_☉) > 9.75. Comparing with Fig. 3, there are clear differences between the SDSS and VVDS populations. First, the tight blue sequence in SDSS contrasts greatly with the cloud in the VVDS sample. In part this is due to the smaller errors on the spectral indices, but it may also be due to a more ‘quiescent’ mode of star formation in galaxies at low redshifts. The second notable difference is that the entire population is older (larger PC1). Finally, we can see that there are fewer strong PSB galaxies, despite the enormous increase in overall sample size.

6.3 Mass density of post-starburst galaxies at z ∼ 0.07

We identify six PSB galaxies using the same criteria as for the VVDS sample, although from Fig. 11 these are clearly only the tip of a distinct and identifiable population. The spectra of the three PSB galaxies above the mass limit of log(M/M_☉) > 9.75 are shown in Fig. 12. The SDSS sample has a high-mass completeness even below this mass limit, but for the purposes of comparison we retain the same mass limit as for the VVDS data set. The number density of PSBs at z ∼ 0.07 is 5.1 × 10^{-7}, i.e. a factor of 200 lower than in the VVDS survey at z ∼ 0.7. For comparison, over the same redshift range the number density of ultraluminous IR galaxies (ULIRGs) decreases by a factor of ∼30 (Kim & Sanders 1998; Cowie et al. 2004).

The total completeness-corrected mass of the SDSS PSB galaxies with log(M/M_☉) > 9.75 is 6.9^{+1.4}_{-1.3} × 10^{10} M_☉, giving a mass density of 1.2 ± 0.2 × 10^{4} M_☉ Mpc^{-3}. This is just 0.43 per cent of the mass density of PSBs at z ∼ 0.7.

As in Section 5.3, an upper limit on the time the PSBs are visible for is 0.6 Gyr. Following equation (3), we find a mass flux of \( \dot{\rho}_{A \rightarrow Q, \text{PSB}} > 2.0 \pm 0.4 \times 10^{-3} M_☉ \text{Mpc}^{-3} \text{yr}^{-1} \). Assuming our best estimate for the visibility of the PSB galaxies of 0.35 Gyr results in a mass flux of \( \dot{\rho}_{A \rightarrow Q, \text{PSB}} = 3.4 \pm 0.6 \times 10^{-3} M_☉ \text{Mpc}^{-3} \text{yr}^{-1} \).

The SED-fitting results indicate that two of the low-redshift PSB galaxies have no residual star formation (SSFR < 10^{-11} yr^{-1}), while one has a SSFR of 10^{-10} yr^{-1}. However, we caution that with only the optical and NIR bands, these values are less reliable than for the VVDS galaxies with UV–IR coverage. We have therefore used all three galaxies to calculate the present-day mass flux through the PSB phase. The masses of the three SDSS PSB galaxies are log(M/M_☉) = 10.25, 10.15 and 10.05, similar to the masses of the VVDS PSB galaxies.

We can compare our low-redshift PSB mass flux to that calculated by Martin et al. (2007) for galaxies in the green valley. They assumed that green valley galaxies defined in NUV-r colours in an SDSS/GALEX-matched catalogue are all entering the red sequence (i.e. all the mass flows from blue to red) to calculate a transition mass flux of \( \dot{\rho}_T = 0.033 M_☉ \text{Mpc}^{-3} \text{yr}^{-1} \). Clearly, this value is considerably greater (a factor of 1000) than our PSB mass flux. If the assumption that all green valley galaxies are heading towards the red sequence is correct, then the PSB pathway to the red sequence appears truly unimportant in the present-day Universe. Some of this discrepancy may be reduced by appealing to the differing mass limits of the two samples. For example, Quintero et al. (2004) studied a sample of PSB galaxies in the SDSS, using a similar magnitude limit to that of Martin et al. (2007), which includes many lower mass
galaxies than in our sample. They measured the ‘rate density’ for PSB galaxies in the SDSS, i.e. the number of galaxies which pass through the PSB phase, to be $\sim 4 \times 10^{-5} \text{Mpc}^{-3} \text{Gyr}^{-1}$. The equivalent value for our high-mass sample is $\sim 1.5 \times 10^{-6} \text{Mpc}^{-3} \text{Gyr}^{-1}$ strongly suggesting that the measured PSB mass flux would increase were we to relax our mass limit.

7 DISCUSSION: ARE POST-STARBURST GALAXIES IMPORTANT?

In this paper, we have presented a sample of galaxies with strong Balmer absorption lines and, through comparison with simulations, have argued that these are the likely descendants of gas-rich major mergers. The strength of their spectral features suggest that they are PSB galaxies with burst mass fractions of at least 5–10 per cent. However, irrespective of whether a starburst has occurred, it is certain that their star-formation has been quenched quickly with a time-scale of $\lesssim 0.1$–$0.2 \text{Gyr}$. As discussed briefly in Section 1, such fast quenching times are generally associated with supernovae feedback after periods of rapid star formation induced by galaxy collisions. An alternative scenario may be the rapid fuelling of star formation in galaxies from filamentary cold-gas flows (Kereš et al. 2005; Ocvirk, Pichon & Teyssier 2008), although direct comparisons with the outputs of these simulations would be required to test this.

7.1 QSOs and post-starburst galaxies

One popular theory for the origin of the red sequence and the relation between galaxy bulge mass and central supermassive BH mass is through the triggering of massive outflows driven by the central BH. Such outflows would quickly halt star formation and therefore the theory suggests an evolutionary link between QSOs and PSB galaxies. It is therefore of interest to compare the number density of the PSB galaxies to that of QSOs at the same redshift. Any meaningful comparison requires knowledge of the QSO lifetime and the visibility time of the PSB galaxies. The former has been estimated using a variety of methods to be $t_{\text{QSO}} \sim 10^7$ (see e.g. Gonçalves, Steidel & Pettini 2008) and we assume $t_{\text{PSB}} = 0.35 \text{Gyr}$ as previously. Setting

\[
\frac{\phi_{\text{QSO}}(M < M_X)}{t_{\text{QSO}}} = \frac{\phi_{\text{PSB}}}{t_{\text{PSB}}},
\]

we can estimate the magnitude limit of the QSOs, $M_X$, which leads to a space density matching the observed space density of PSB galaxies of $1 \times 10^{-4} \text{Mpc}^{-3}$. Using the parametrized QSO luminosity function of Croom et al. (2004) at $z = 0.7$, we find $M_X \approx M^* + 1.5$ where the magnitudes are $b_J$ band and Vega zero-point. The number density of strong PSB galaxies coincides with that of moderately powerful QSOs, 1.5 mag fainter than $M^*$, does not of course necessarily imply an evolutionary link. The AGN luminosity function continues to rise to fainter magnitudes (Hao et al. 2005) and uncovering the triggering mechanisms of AGN as a function of luminosity remains one of the biggest observational challenges for extragalactic astronomy.

The number density of the PSB galaxies evolves rapidly. Extrapolating the evolution of the QSO luminosity function of Croom et al. (2004) to $z = 0.07$, and taking $t_{\text{QSO}} \sim 10^9$ as before, we find a QSO number density of $3.1 \times 10^{-5} \text{Mpc}^{-3}$ above the same magnitude limit of $M_X = -22.2$, a factor of a few below the $z = 0.7$ number density. So, current results suggest that the evolution in number density of QSOs is not as strong as the evolution in the PSB number density. To our knowledge, an observed QSO luminosity function at $z \sim 0$ is not currently available, and would be required for a more detailed comparison.

7.2 Major mergers and post-starburst galaxies

If, as we have suggested, the strong PSB galaxies selected in this paper are the result of major mergers, it is instructive to compare the number of PSB galaxies to the number of close galaxy pairs in the same survey volume. de Ravel et al. (2008) measure the fraction of close spectroscopic pairs to derive the merger rate using the same VVDS galaxy sample as in this paper. For galaxies with $\log(M/M_\odot) > 10$, they derive a merger rate of $2 \times 10^{-4} \text{Mpc}^{-3} \text{Gyr}^{-1}$, with a magnitude difference criterion such that they are sensitive to mergers with mass ratios $\gtrsim 4:1$. This can be compared with the number of PSB galaxies, divided by the time during which they are detectable i.e. $2.9 \times 10^{-4} \text{Mpc}^{-3} \text{Gyr}^{-1}$ for $t_{\text{PSB}} = 0.35 \text{Gyr}$. Given the small number statistics of both samples, uncertainty in both merger and PSB time-scales and the problem of the unknown magnitude difference between the PSB progenitors, it is encouraging that these numbers are so close. Of course, larger samples and further detailed observations of the PSB galaxies will greatly aid our understanding of their origin and possible link to gas-rich major mergers. As with the QSO number density, the current estimates of the evolution in merger rate with redshift show less evolution than observed in the PSB number density. Although de Ravel et al. (2008) find that the evolution with redshift is stronger for lower luminosity and lower mass galaxies, with the merger rate decreasing by a factor of 2 between a redshift of 1 and 0.5, this is still not as strong as the evolution in PSB number density. Finally, we note that out of the 36 close galaxy pairs identified by de Ravel et al. (2008) one galaxy is part of the PSB sample of this paper. Given the small probability of a chance coincidence, this suggests that in at least one case the PSB stellar population is linked with tidal disruption caused by an ongoing major merger.

The strong evolution in PSB number (and mass) density compared to the evolution of both QSO number density and galaxy major merger rate leads us to the question of what may cause such a sharp decline in the number of PSB galaxies. Through our comparison with merger simulations, we have identified two important factors in creating a PSB galaxy: gas mass fraction and time-scale of the starburst. Larger gas mass fractions provide more fuel for the starburst, leading to stronger and more prolonged PSB signatures. Because gas is used up in the formation of stars, it is reasonable to assume that gas mass fraction decreases with decreasing redshift, a fact that may play a leading role in the global decrease of star formation rate density since $z \sim 1$. A second effect is the starburst time-scale, which is generally assumed to be linked to the disc dynamical time-scale, which in turn is linked to the dynamical time of the halo. This latter value is known to increase with redshift, by a factor of 2 between a redshift of 1 and 0 (Neistein private communication; Barkana & Loeb 2001). A lengthening of the duration of the starbursts, together with a decreasing amount of fuel available, may be the dominant mechanism responsible for the decrease in number density of PSB galaxies. Clearly further simulations will be required to test these ideas.

7.3 The environments of PSB galaxies

Given the possible link of PSB galaxies to gas-rich major mergers, it is interesting to investigate the local environments of the galaxies. Cucciati et al. (2006) measured the density on 5 and 8 h⁻¹Mpc scales around galaxies in the VVDS survey. Of the 16 PSB galaxies
with \( \log(M/M_\odot) > 9.75 \). 15 have available density measures. A control sample of 2122 VVDS galaxies with good-quality redshift flags was selected for comparison. We do not detect any significant difference in the mean or median densities around the PSB galaxies, in agreement with the results of Yan et al. (2008). It is, however, interesting to see that the spread in local density values for the PSB sample is very large. In detail, three lie in underdense environments \((\delta_s < 0)\), nine in normally overdense environments \((0 < \delta_s < 1)\), while the median value for the control sample is \(\delta_s = 0.44 \pm 0.02\) and three in strongly overdense environments \((\delta_s > 1)\). Furthermore, there is no clear trend between star-forming versus non-star-forming PSB galaxies. The presence of PSB galaxies in all types of environment will be an important constraint for understanding their origin and evolution.

7.4 Building the red sequence through post-starburst galaxies

In Section 5.3, we compared the mass flux through the PSB phase to the mass buildup of the red sequence as measured by Arnouts et al. (2007). We found a value of \(-40\) per cent for PSBs with no residual star formation, or \(80\) per cent for all PSBs with \(\log(M/M_\odot) > 9.75\). These numbers, although consistent (i.e. not greater than \(100\) per cent), perhaps still appear surprisingly high if we expect other quenching mechanisms with slower time-scales to also play a role in moving mass on to the red sequence (van den Bosch et al. 2008). The key question is whether there is a one-way flow of galaxies from the blue to the red sequence? What prevents a galaxy from restarting star formation due to subsequent inflow of gas after experiencing a major merger? SPH simulations of galaxy mergers involve strong mechanical AGN feedback to prevent subsequent star formation and allow the galaxy to remain on the red sequence. The large amount of mass flowing to the red sequence through the PSB phase at high redshift may in fact cause us to question the fact that strong mechanical feedback is effective in the long term for the majority of galaxies. Semi-analytic cosmological models provide one method to test galaxy formation scenarios in a full cosmological context and could help to understand the directions of mass fluxes. A full comparison of the recent star formation histories of the VVDS and SDSS galaxies presented in this paper with semi-analytic models is underway. A full census of different types of transition galaxies as a function of redshift, when combined with accurate measurements of the mass densities on the blue and red sequence, will help to reveal the true importance of mechanical gas expulsion mechanisms (feedback) on the global evolution of the galaxy population.

We have found that strong PSB galaxies have stellar masses similar to those of the least massive galaxies on the red sequence. This has important implications for our understanding of the physical processes involved in the buildup of the red sequence, and in particular the subsequent role of dry mergers in forming the shape of the red-sequence mass function observed today (Bell et al. 2006; Naab et al. 2006).

8 SUMMARY

Using a PCA analysis of the spectra of the VVDS deep spectroscopic galaxy survey, we have selected a sample of 16 galaxies with strong Balmer absorption lines at \(0.5 < z < 1.0\) and above a mass completeness limit of \(\log(M/M_\odot) > 9.75\). Through comparison with a suite of SPH merger simulations and toy starburst models, we have shown that these galaxies are likely to have undergone a strong starburst within the last few tenths of a Gyr, with burst mass fractions of the order of \(10\) per cent, similar to those derived for LIRGS at these redshifts (Marcillac et al. 2006). The key requirement for the observation of the PSB galaxies is a fast quenching time-scale of \(\lesssim 0.1 \pm 0.2\) Gyr. We show that there is a maximum visible lifetime for the PSB galaxies of \(0.6\) Gyr, but for lower gas mass fractions of \(\sim 20\)–\(40\) per cent a lifetime of \(0.35\) Gyr is more likely.

The key results of this paper are

(i) **Number density:** PSB galaxies with \(\log(M/M_\odot) > 9.75\) have a number density of \(10^{-4}\) Mpc\(^{-3}\). Assuming they are visible for an average of \(0.35\) Gyr, and that a QSO shines for \(10^7\) years, this is equal to the number density of QSOs brighter than \(M^* (z = 0.7) = 1.5\) (Croom et al. 2004).

(ii) **Masses and mass density:** summing all the mass in the PSB population gives a mass density of \(\log(\rho^* M^{-1}\) Mpc\(^{-3}\)) = 6.43 \pm 0.06. The mass distribution of the PSB galaxies rises to the mass completeness limit of \(\log(M/M_\odot) > 9.75\), therefore measuring the complete mass distribution for PSB galaxies at \(z \approx 0.7\) will require a deeper survey. The true mass distribution is crucial for understanding the relative importance of different mechanisms for causing PSB galaxies (Kaviraj et al. 2007).

(iii) **Mass flux:** we select the five PSB galaxies with no residual star formation according to multiwavelength SED fitting. Taking \(6.6\) Gyr as an upper limit on the visibility time of the PSB galaxies gives a lower limit on the mass flux of \(\dot{\rho}_{A \rightarrow Q, PSB} > 0.0022^{+0.0004}_{-0.0006} M_\odot\) Mpc\(^{-3}\) yr\(^{-1}\). Taking the best estimate for \(\dot{\rho}_{PSB}\) of \(0.35\) Gyr gives \(\dot{\rho}_{A \rightarrow Q, PSB} = 0.0038^{+0.0004}_{-0.0001} M_\odot\) Mpc\(^{-3}\) yr\(^{-1}\). Comparing this to the rate of buildup of the red sequence (Arnouts et al. 2007), we find \(38^{+4}_{-11}\) per cent of the growth of the red sequence at \(z < 1\) takes place from galaxies which have passed through the strong PSB phase, assuming all these galaxies subsequently remain on the red sequence.

(iv) **Environment:** we use the local density on \(5 h^{-1}\) Mpc scales from Cucciati et al. (2006) to show that PSB galaxies are found in all environments, from underdense to strongly overdense.

(v) **Low versus high z:** we compare our high-redshift results to a sample of galaxies with \(0.05 < z < 0.1\) selected from the SDSS and UKIDSS. Despite the enormous increase in sample size, only three PSB galaxies of the same strength as in the VVDS sample are detected for the same mass limit. We find the mass density of strong PSB galaxies decreases by a factor of \(230\) and number density by a factor of \(200\) from \(z \sim 0.7\) to \(0.07\) (see also Hammer et al. 1997; Le Borgne et al. 2006).

This paper finds that PSB galaxies, although rare in the local Universe, are of global importance at higher redshift. With larger and deeper spectroscopic surveys, exciting new constraints could be obtained on the processes which drive galaxy evolution. The joint analysis of imaging and spectroscopy will help to break observational degeneracies, especially when combined with ‘observations’ of galaxy simulations. On the advent of an era of large broad-band photometric surveys, it is important not to forget the wealth of additional information on galaxy evolution available from the additional investment in spectroscopy.

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