Lyman break galaxy close and interacting pairs at $z \sim 3$

Jeff Cooke, Joel C. Berrier, Elizabeth J. Barton, James S. Bullock and Arthur M. Wolfe

1Department of Physics & Astronomy, Center for Cosmology, University of California, Irvine, Irvine, CA 92697, USA
2Department of Physics, Center for Astrophysics and Space Sciences, University of California, San Diego, La Jolla, CA 92093, USA

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ABSTRACT

Investigations of interacting and merging galaxies at high redshift are vital to our understanding of their formation and evolution. To date, the identification of interactions at $z \sim 3$ and above has relied on rest-frame ultraviolet morphological parameters. Here, we present five serendipitous spectroscopic $z \sim 3$ Lyman break galaxy (LBG) pairs with projected proper separations $<15\ h^{-1}\ kpc$ in our survey of nine separate deep Keck fields. The data consist of 140 of our highest signal-to-noise ratio LBG spectra and $\sim 500$ of our most confident colour-selected LBGs. We show that the pairs are composed of two distinct close and/or interacting LBGs from a detailed analysis of the rest-frame ultraviolet 1D and 2D spectra and the deep broadband images. In addition, we show that the number and separation distribution of the pairs is expected from (1) the two-point angular correlation function when applied to the LBG pair separation distribution in our survey and $\sim 2500$ colour-selected LBGs from the literature and (2) an analysis of a carefully matched high-resolution hybrid numerical and analytical cosmological simulation. Because the spectroscopic slitlets have random orientations with respect to the close pairs on the sky, the serendipitous pairs provide an unbiased sampling of the underlying close pair fraction. Finally, we discover two Ly$\alpha$ emitters (LAEs) in our slitlets and find that they reside within 50 projected $h^{-1}\ kpc$ of the spectroscopic LBGs. In this work, we uncover a strong relationship between Ly$\alpha$ emission and pair separation. All confirmed and all candidate LBG pairs with separations of $\leq 15\ projected\ h^{-1}\ kpc$ exhibit Ly$\alpha$ in emission and we find an indication of an overabundance of Ly$\alpha$ emission in pairs with $\leq 50\ projected\ h^{-1}\ kpc$ separations. This relationship suggests a picture in which a measurable fraction of the Ly$\alpha$ emission of LBGs, and potentially LAEs, is generated via interaction mechanisms such as triggered star formation and the dispersal of obscuring gas and dust. As a result, serendipitous spectroscopic close pairs provide a unique means to help identify and study high-redshift galaxy interactions using ground-based optical data.

Key words: methods: observational – galaxies: evolution – galaxies: formation – galaxies: high-redshift – galaxies: interactions.

1 INTRODUCTION

A fundamental prediction of $\Lambda$ cold dark matter ($\Lambda$CDM) models of structure formation is the hierarchical build up of galaxies via mergers with a rate that declines over time (e.g. Cole et al. 2000, and references therein). Observations of this process at low and high redshift are necessary to test these predictions, assess the effects of interactions, and to help clarify our current understanding of galaxy assembly. Close interactions and mergers act to trigger star formation and contribute to the accretion of matter and the morphological transformation of galaxies over time (e.g. Larson & Tinsley 1978; Keel et al. 1985; Mihos & Hernquist 1996; Barton, Geller & Kenyon 2000; Steinmetz & Navarro 2002; Barton, Geller & Kenyon 2003; Scannapieco & Tissera 2003, and many others).

In practice, however, identifying and studying mergers and interactions are difficult, largely because definitions vary, tidal features and interaction indicators can be faint, and morphologies are difficult to quantify. At higher redshifts ($z \gtrsim 1$), this is more challenging as galaxies become fainter and less resolved. Although non-parametric methods have been developed to characterize the morphology of high-redshift systems (Conselice et al. 2003; Lotz et al. 2006; Law et al. 2007), such analyses are best done using the superior efficiency and resolution of optical data but, as a...
result, contribute an additional complication of linking the observed clumpy and chaotic rest-frame ultraviolet (UV) to the better understood rest-frame optical morphology.

The Lyman break galaxies (LBGs) detected by the Lyman break colour-selection technique (Steidel et al. 1996) are a well-studied population of galaxies at high-redshift. Deep Hubble Space Telescope (HST) images of \( z > 2 \) LBGs in surveys such as the Great Observatories Origins Deep Survey (GOODS), Cosmic Evolution Survey (COSMOS) and the Ultra Deep Field (UDF) show a wide range of rest-frame UV morphologies — from single compact or diffuse systems to multiple compact star-forming components with, or without, diffuse emission (e.g. Law et al. 2007; Rafelski et al., in preparation). The latter morphology has been interpreted as either star-forming regions within a single coalescing galaxy and/or the result of interactions or mergers.

Because of the faint nature of \( z \sim 3 \) LBGs (\( L_\star \) corresponds to \( m_\star \sim 24.5 \)), low-resolution spectroscopy can only achieve a signal-to-noise ratio (S/N) of a few with 8-m class telescopes for galaxies with \( m_\star < 25.5 \) using reasonable integration times. This limitation prohibits detailed investigations of individual LBGs. Except for the very brightest cases, detailed studies require composite spectra and/or rare gravitationally lensed systems. Composite spectral analysis (e.g. Shapley et al. 2003) has provided great insight into the average properties of LBGs but dilutes the features and relationships particular to individual systems. Gravitationally lensed LBG systems provide magnified flux that boosts the S/N of individual systems, but the total number of these systems is small, their reconstruction analyses are subject to model constraints, and their chance discoveries do not allow a study at desired redshifts.

Recently, infrared integral field observations using adaptive optics have been very informative on the kinematics of a sample of \( z \sim 2 \) LBGs (e.g. Förster Schreiber et al. 2006; Law et al. 2007; Shapiro et al. 2008; Wright et al. 2009) from prominent rest-frame optical features. Although this approach has been effective on relatively luminous LBGs, it would be prohibitively time consuming to compile a statistical sample of typical (including faint) systems using existing instruments. Moreover, this method becomes increasingly difficult for higher redshift populations as key features are shifted out of the range of wavelength sensitivity. As a result of the above limitations, a clear and consistent interpretation of the morphological and spectroscopic effect of mergers and interactions of typical LBGs at \( z \gtrsim 3 \) via conventional approaches lay beyond the sensitivity thresholds and capabilities of current ground-based adaptive optics (AO)-assisted or space-based observations.

A standard method to identify a large number of merger and interacting galaxy candidates at low- to intermediate redshift and to avoid many of the difficulties in morphological classification and interpretation is to measure the galaxy close pair fraction (e.g. Patton et al. 2000, 2002; Lin et al. 2004; Berrier et al. 2006; Kartaltepe et al. 2007; Lin et al. 2007). Galaxy pairs with observed separations of \(<50 h^{-1} \text{kpc}\) and velocity offsets of \(\pm 500 \text{ km s}^{-1}\) are likely to interact and/or merge and can be more easily and consistently observed and quantified. Moreover, galaxies found in close pairs at high redshift have a higher likelihood of an imminent merger than at low redshift based in part on the fact that there are fewer galaxy clusters (e.g. Berrier et al. 2006). As a result, close pairs at high redshift provide a means to identify galaxies that are interacting or are destined to interact on a short time-scale and a strong constraint on the merger rate. Finally, the detailed behaviour of close pairs can be tracked in matched high resolution cosmological simulations to glean information beyond that of the observations.

Although the expected number of LBGs in close pairs can be inferred photometrically from the observed angular correlation function, spectroscopy is necessary to help differentiate actual close pairs from false pairs that have small projected separations on the sky. In order to gather a large number of LBG spectra, nearly all surveys to date have utilized optical low-resolution multi-object spectroscopy (MOS). This method uses slitmasks to place slitlets at the locations of selected targets but cannot acquire spectroscopy for objects with very small projected separations on the sky or that conflict in the dispersion direction. While MOS is efficient in acquiring a statistical sample of typical LBGs, this shortcoming makes it difficult or impossible for a single slitmask to acquire information for many of the galaxies closely spaced on the sky. A programme employing a number of overlapping slitmask observations of the same area of the sky could, in principle, resolve this issue. However, we show below that not all close galaxy pairs at \( z \sim 3 \) are easily identifiable from their imaging alone and would introduce systematics in such a time-expensive endeavour.

A different technique, which we introduce here, allows existing MOS data sets to be used to study close and interacting pairs at high redshift. The density and clustering behaviour of LBGs predict that a small fraction of close pairs are expected to fall serendipitously into the area probed by the MOS slitlets. Moreover, because the slitlets in conventional LBG surveys have random orientations with respect to the serendipitous close pairs on the sky, they produce samples unbiased by selection. In this manner, the serendipitous pairs reflect the underlying close and interacting LBG pair behaviour and effectively circumvent the MOS mechanical constraints.

We analyse a conventionally acquired nine-field deep Keck imaging and spectroscopic survey for \( z \sim 3 \) LBGs and find five serendipitous spectroscopic close pairs. We use 509 colour-selected and 140 spectroscopically confirmed LBGs, the large \( z \sim 3 \) photometric LBG data set of Steidel et al. (2003, hereafter S03), and a high-resolution cosmological simulation to investigate the distribution of close pair separations and the expectation of the serendipitous pairs. We present several lines of evidence from a detailed analysis of the imaging and spectroscopic data that support the close pair/interacting nature of the serendipitous detections. We show that the properties of this unique sample, in turn, provide insight into the rest-frame UV properties of the LBG population that are otherwise inaccessible and a means to help identify high-redshift interactions in ground-based data.

This paper is organized as follows. We describe relevant information regarding the data and data acquisition in Section 2. We present the serendipitous spectroscopic interacting pairs, investigate their rest-frame UV behaviour, and compare the results to precedence in the literature in Section 3. Close pair observations and measurements are discussed in Section 4 and the results from the simulation analysis in Section 5. The two Ly\( \alpha \) emitters (LAEs) discovered in our sample are presented in Section 6, and we address the observed relationship between Ly\( \alpha \) in emission and close pair separation in Section 7. Finally, in Section 8, we provide a summary. All magnitudes are in the AB (Fukugita et al. 1996) magnitude system unless otherwise noted. We assume \( \Omega_M = 0.3, \Omega_\Lambda = 0.7, h = 1.0 \) cosmology throughout and list close pair separations in physical (proper) units.

2 OBSERVATIONS

We use the \( z \sim 3 \) LBG survey of Cooke et al. (2005, hereafter C05) for the observational analysis in this paper. The survey consists of deep imaging and spectroscopy of nine widely separated...
fields covering $\sim 460 \text{ arcmin}^2$. Seven fields were imaged using the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995; McCarthy et al. 1998) on the 10-m Keck I telescope with two fields imaged using the Carnegie Observatories Spectrograph and Multi-Object Imaging Camera (COSMIC; Kelts et al. 1998) mounted on the 5-m Hale telescope at the Palomar Observatory. We obtained follow-up spectroscopy of all nine fields using LRIS. The multiple fields suppress the effects of cosmic variance and provide $\sim 800$ colour-selected and $\sim 200$ spectroscopically identified LBGs for statistical analysis. Details of the observations, data reduction, and LBG analysis can be found in C05 and Cooke et al. (2006). Below, we briefly discuss a few relevant specifics of the data.

The $z \sim 3$ LBG candidates in our survey are selected by their $UBVRI$ colours. Although the deep images can select LBGs to fainter magnitudes, we restrict our analysis in this paper to LBGs with $m_B \leq 25.5$ in order to define a sample that has (1) photometry accurate to $\lesssim 0.2$ mag uncertainty in all filters that probe the rest-frame UV continua, (2) follow-up spectroscopy, (3) defined photometric selection functions and (4) a measured spatial correlation function.

The spectroscopic component of our survey follows a conventional approach to gather a large number of $z \sim 3$ LBG spectra using MOS slitsmasks. The survey was not originally designed to study interacting LBGs or to measure close spectroscopic pairs.

The physical constraints of MOS slitsmasks can prevent acquisition of galaxies that are closely spaced on the sky or those that fall in the dispersion direction of the targeted observations. This situation is illustrated in Fig. 1 for two spectroscopically confirmed LBGs and associated colour-selected close pair candidates from our survey. However, because each MOS slit covers a non-negligible area of the sky ($\sim 18 \text{ arcsec}^2$ on average), occasionally a close pair will have a small enough separation or coincidental near alignment to be detected in a slit that was originally intended for a single photometrically identified colour-selected LBG candidate.

The MOS slitlets in our survey were centred on the LBG candidates with position angles near the parallactic angle of the observations to minimize wavelength-dependent flux loss caused by atmospheric dispersion. As a result, this is an unbiased spectroscopic survey for the purposes discussed here because the data were acquired randomly with respect to the orientation of close pairs on the sky. Any detected close pairs in the slitlets are indeed serendipitous and directly reflect the true underlying distribution of close pairs on the scales probed by the dimensions of our slitlets.

The seeing in the images used for colour selection of the LBG sample ranged from 0.6–1.5 arcsec half-width half maximum (FWHM), with those having 0.6–1.0 arcsec FWHM used for pair analysis. In addition, all spectroscopy was acquired under good conditions (0.8–1.2 arcsec seeing FWHM). The slitlets were milled to have 1.0–1.5 arcsec widths, with 6 arcsec minimum and $\sim 14$ arcsec average lengths.

With knowledge that $z \sim 3$ LBGs are near-point sources in ground-based observations, we designed the widths of our MOS slitlets $\sim 0.4$ arcsec larger than the expected seeing FWHM to gather the maximum flux and to compensate for $\sim 0.2–0.3$ arcsec astrometric errors across the focal plane. As a result, the spectral resolution for a given LBG was typically determined by the seeing and is $\sim 400 \text{ km s}^{-1}$ FWHM for most observations.

### 3 SERENDIPITOUS SPECTROSCOPIC CLOSE PAIRS

In the full spectroscopic data set, we discover LBGs that exhibit unexpected double Ly$\alpha$ emission in the 2D spectra with double or overlapping continua. These data form distinct double Ly$\alpha$ emission peaks in the merged 1D spectra. In addition, we find that these objects show double morphology (two measurably separated flux peaks) in the broad-band images. Furthermore, we find that the Ly$\alpha$ emission and continua in the 2D spectra have a one-to-one correspondence in the spatial direction when compared to the separations of the flux peaks in the images. We term these objects `serendipitous spectroscopic close pairs’ (SSCPairs).

A systematic analysis the images, 2D spectra, and 1D spectra of 140 of our highest S/N spectroscopically confirmed $z \sim 3$ LBGs finds five such systems that show compelling evidence for more than one identified major component. We discuss the observed properties of the five SSCPairs in the following sections. Because the separations for some of the SSCPairs cause them to be unresolved by the source extraction routine SExtractor (Bertin & Arnouts 1996) in the ground-based images, we adopt a naming convention that uses the RA of the targeted field and the identification number assigned by SExtractor for the originally targeted LBG. For the SSCPairs that were detected as two distinct LBGs by SExtractor, we label the pair using the RA of the field and the identification number of the targeted LBG only. Fig. 2 displays the ground-based LRIS $R$-band images and 2D spectra of these systems. Object 1643–2377 received follow-up higher S/N, higher resolution longslit spectroscopy using LRIS (Cooke et al. 2008). These data provide valuable insight into LBG close pair properties and are used below to help confirm our analysis methods of the low-resolution, low S/N SSCPair spectra.

For the results presented here, including those from the simulation and close pair analysis, we use the parameters of the low-resolution data of 1643–2377 for consistency.

In addition to the five SSCPairs, we find six LBG close pair candidates with separations $\sim 15 \text{ h}^{-1} \text{kpc}$. These were not included...
Close galaxy pairs at z \sim 3

Figure 2. Ground-based R-band images and 2D spectra of the five spectroscopic z \sim 3 LBG close pairs, the SSCpairs. Each image is \sim 15 arcsec on a side and the labelled rectangle replicates the slitlet dimensions and orientation for that particular observation. Directly below each image is a section of the corresponding 2D spectrum centred on the Ly\alpha feature. Top: SSCpairs 0056–0635 (0056–0635 and 0056–0632) and 0336–1250. Centre: SSCpairs 1013–1182 and 1643–2377. Bottom: SSCpairs 0957–941 (0957–0941 and 0957–0961). The SSCpairs are named after the original targeted LBG. Objects 0056–0635 and 0056–0632 are detected as separate colour-selected LBGs but are referred to as 0056–0635 and 0056–0632 for consistency.

R-band images probe z \sim 3 LBG UV continua near rest-frame \sim 1700 \AA. Although faint, the 2D spectrum of 0056–0635 shows distinct continua and Ly\alpha emission for objects 0056–0635 and 0056–0632.

Figure 3. Ground-based R-band images and 2D spectra of four z \sim 3 LBG <15 h^{-1} kpc close pair candidates. These four candidates, and the two candidates shown in Fig. 1, were not included in the SSCpairs analysis because the bulk of the flux from the secondary component fell outside of the slitlet dimensions. Top: objects 0336–0380 and 1643–1687. Bottom: objects 2342–2525 and 1057–2469. The photometric close pair candidates are circled and labelled in the images. Object 1057–2469 is two objects, the fainter of which is the photometric candidate. As in Fig. 2, each image is \sim 15 arcsec on a side and the labelled rectangle replicates the slitlet dimensions and orientation for that particular observation. The images were obtained using LRIS except object 2342–2525 which was obtained using COSMIC. The four LBGs here, and two in Fig. 1, display dominant Ly\alpha emission as SSCpairs by definition because the bulk of the emission of the secondary galaxy did not fall into the dimensions of the slitlet. Four of the six SSCpair candidates are shown in Fig. 3, with the remaining two shown in Fig. 1. Future spectroscopy will determine whether the six candidates are indeed associated.

The small separations and overlap of the faint SSCpair spectra make the clean extraction of individual components difficult. As a result, we present the merged spectra\(^1\) in Fig. 4, along with spectral segments focusing on the Ly\alpha features. Presented in this way, the two components of each system can be directly compared, but have blended noise, continua and features that include absorption effects from the Ly\alpha forest blueward of Ly\alpha emission. Each component of the SSCpairs shows Ly\alpha in emission and we show in Section 3.2 that this is not a selection bias. The presence of Ly\alpha emission from each component results in double-peak Ly\alpha emission profiles for all five merged SSCpair spectra.

We remark that the double-peak Ly\alpha emission features result from merging the spectra and differ from the double-peak Ly\alpha feature predicted for a static or expanding shell of gas arising from a single LBG (e.g. Tenorio-Tagle et al. 1999; Mas-Hesse et al. 2003;\(^1\)Pair 0957–0941 has the largest separation of the SSCpairs. We made efforts to extract the individual components of the low S/N spectra using conventional routines, but found each spectrum was contaminated with a non-negligible amount of flux from the other galaxy. We present the merged spectra for this pair in Fig. 4 for consistency.

\(^1\)Pair 0957–0941 has the largest separation of the SSCpairs. We made efforts to extract the individual components of the low S/N spectra using conventional routines, but found each spectrum was contaminated with a non-negligible amount of flux from the other galaxy. We present the merged spectra for this pair in Fig. 4 for consistency.
Figure 4. Left-hand panels: spectra of the five LBG serendipitous spectroscopic close pairs shifted to the rest-frame and box-car smoothed by 3 pixels. As discussed in the text, these spectra are the merged 1D spectra of the two very close or overlapping spectra. Although this aids in the identification and comparison of the systems, it blends and can dilute the significance of individual galaxy features. Dashed (blue) and dotted (maroon) vertical lines mark the prominent ISM transitions of the apparent lower and higher redshift galaxy, respectively, and are labelled. For clarity, not all lines used in the fit are shown. The red (grey) curve reflects the 1σ per pixel error array, the green (light grey) horizontal line indicates zero flux, and the thick solid (grey) vertical lines mark the positions of bright night sky emission lines. Right-hand panels: 1D spectral segments of the five pairs (not smoothed) that focus on a 24 Å region (rest frame) centred around the merged double-peak Lyα emission features.

Verhamme, Schaerer & Maselli 2006; Verhamme et al. 2008). We describe below that the Lyα emission features of the SSCpairs do not result from single galactic-scale expanding shells as is evidenced by the two spatially offset Lyα emission peaks and continua in each SSCpair 2D spectrum, double morphology, and the direct correspondence between the spatial offsets of the 2D Lyα features and continua and the flux peaks in the images. We note that an accurate measurement of the small Lyα emission velocity offset in the 1D spectra of SSCpair 1643–2377 is difficult. In that case, we used the high-S/N, higher resolution spectroscopic data (Fig. 5) to cleanly measure the Lyα peak offset and find that the measurement agrees with our low-resolution value within the uncertainty.

Table 1 lists the relevant information of the five SSCpairs. All reported velocity differences between the two components are corrected for offsets in wavelength resulting from their spatial separation as determined by the associated flux peaks in the images (Section 3.2). We see that the two components have projected physical separations of ~3–13 h^{-1} kpc in the images and 2D spectra. We remark that because these are projected separations, they represent the minimum actual separations.

O and B stars are largely responsible for the rest-frame UV flux over the wavelengths probed by the optical broad-band filters used in this survey. As a result, we interpret the continua and emission lines

Figure 5. Spectra comparing the Lyα emission for 1643–2377 obtained with two different resolutions. Left-hand panel: the merged low-resolution discovery spectrum (~9 Å resolution). Right-hand panel: the higher signal-to-noise higher resolution (~4 Å resolution) follow-up spectrum showing two distinct peaks.
from the each SSC pair component as a major young star-forming region or a distinct LBG. In the following sections, we discuss whether the results favour an interpretation that the SSC pairs are coalescing single massive galaxies with two violent starbursts or an interpretation that the SSC pairs are two separate close and/or interacting galaxies. The lines of evidence presented below argue that these are separate components that are inconsistent with the single galaxy interpretation. We use morphological and spectroscopic information obtained from the SSC pairs, space-based investigations of local LBG analogues, LBG ground- and space-based observations and relationships found in the literature to help interpret the SSC pairs and to help shed light on the rest-frame UV behaviour of LBGs.

### 3.1 Morphology

Space-based images of $z \sim 3$ LBGs (e.g. Law et al. 2007) show a wide range of morphologies, such as concentrated single nucleated sources, multiple nucleated sources, and diffuse structures. Although complex, typical LBGs have half-light radii of $\lesssim 0.3$ arcsec (Gardner, Brown & Ferguson 2000; Ferguson et al. 2004) or $\lesssim 2$ h$^{-1}$ kpc, and appear as near-point sources in ground-based images. We inspect the flux contours of the SSC pairs in the LRIS ground-based $u' B V R I$ images for departures from an unresolved source in the form of significant extended features, elongations, or objects with more than one discernible flux peak.

The $V R I$ broad-band filters probe the star-forming rest-frame continuum of the $z \sim 3$ LBG sample longward of Ly$\alpha$. We find that the centroids of the flux peaks in the ground-based $V R I$ images are accurate to $\sim 0.4$ arcsec (approximately the seeing FWHM) aided by the near point-source profiles of LBGs. Each LBG that meets the 2D and 1D criteria discussed below exhibits two measurably separated flux peaks in the $V R I$ images and have projected centroid separations of $\sim 3-13$ h$^{-1}$ kpc. The separations for SSC pairs 1013–1182 and 1643–2377 are at or near the resolution limit. The double nature of 1013–1182 relies largely on other measurements presented in this work such as the two spatially offset Ly$\alpha$ emission peaks in the 2D spectra. For 1643–2377, the high S/N from the intrinsic luminosity of this system allows a secure centroid measurement. Finally, we note that the broad-band continuum luminosity and Ly$\alpha$ emission from each SSC pair component falls in the range of typical $m_R \lesssim 25.5$ LBGs at $z \sim 3$. Consequently, each SSC pair component has LBG-equivalent estimated star formation rates ($\sim 10^{-2} - 10^{-3}$ M$\odot$ yr$^{-1}$, Papovich, Dickinson & Ferguson 2001; Shapley et al. 2001, 2003).

At low to intermediate redshifts, the UV and optical studies of compact UV-luminous galaxies (UVLGs; e.g. Heckman et al. 2005; Grimes et al. 2007; Overzier et al. 2008, hereafter O08) have made great strides in our understanding the observed LBG UV morphology at high redshift. UVLGs are in every practical way local analogues to LBGs having similar mass, gas content, half-light radii, UV colours, metallicity and star formation rates. O08 find that although the objects in their sample do not show convincing evidence for mergers or interactions from the $HST$ rest-frame UV imaging alone, every UVLG in their sample shows evidence of interaction in the rest-frame optical images. They conclude that mergers are the main mechanism for the observed star formation in these systems and find that the bulk of the star formation arises in several compact ($\sim 100-300$ pc) regions.

O08 deconvolve the pixel scale and dim the surface brightness of their $z \sim 0.1$ UVLG sample to match the depth and resolution of $z \sim 3$ LBG observations in the GOODS, COSMOS and UDF fields. The multiple bright star-forming regions of the UVLGS blend into 1–3 bright clumps with separations of $\lesssim 0.5$ arcsec when redshifted to $z \sim 3$ and accurately reproduce the space-based morphology of LBGs. For the ground-based image resolution in our survey, these clumps would appear as a single near-point source for all but the most separated cases, which would be detected as SSC pairs depending on component properties. Perhaps the most convincing evidence of this is the case of SDSS J080844.26+394852.4 (hereafter UVLG 0808) in the O08 sample.

We find that all UVLGS in the O08 sample, except for UVLG 0808, have compact rest-frame UV morphologies and, if placed at $z \sim 3$, would be detected as single near-point sources in our survey.

### Table 1. Serendipitous spectroscopic close pairs.

| Pair      | RA$^a$   | Dec.$^a$ | $m_R$ | $z_{Ly\alpha}^b$ | $z_{ISM}$ | $\Delta v_{Ly\alpha}^e$ | $\Delta v_{ISM}^d$ | Slit$^d$ | $\Delta r^c$ | Seeing$^g$ |
|-----------|----------|----------|-------|------------------|-----------|-------------------------|------------------|---------|-------------|-----------|
| 0056−0635 | 00:59:27.722 | +01:41:37.37 | 25.0, 25.2 | 3.367,3.386 | 3.363,3.374 | 870 | 350 | 1.5 | 9.5 | 0.8; 1.4 |
| 0336−1250 | 03:39:17.199 | −01:31:29.10 | 23.4 | 2.824,2.845 | 2.819,2.835 | 960 | 575 | 1.5 | 8.2 | 0.9 − 1.1; 0.6 |
| 0957−0941 | 09:57:48.414 | +33:11:28.43 | 24.8, 25.0 | 2.680,2.688 | 2.678,2.685 | 480 | 400 | 1.5 | 13.3 | 0.9; 1.0 |
| 1013−1182 | 10:15:57.234 | +00:21:55.06 | 24.6 | 2.779,2.792 | 2.775,2.786 | 730 | 555 | 1.3 | 2.6 | 0.9; 0.9 |
| 1643−2377b | 16:44:38.314 | +46:27:08.23 | 22.2 | 3.036,3.044 | 3.029,3.036 | 430 | 360 | 1.5 | 4.7 | 0.8; 0.7 |

$^a$Coordinates of the LBG flux centroid used to mill the multi-object spectroscopic slit.

$^b$Assigned redshifts for the respective features of the two identified components.

$^c$Velocity offset in km s$^{-1}$ between the respective features, corrected for angular separation.

$^d$Width of multi-object spectroscopic slit in arcsec.

$^e$Projected angular component separation in the images in physical kpc.

$^f$Spectroscopic FWHM in arcsec derived from night sky emission lines; R-band seeing FWHM in arcsec.

$^g$Integrated magnitude of both sources.

$^h$Values are from the low-resolution data for consistency.

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$^2$LBGs at $z \sim 3$ are colour-selected as $u'$-band ‘drop-outs’ because the decrement in their continua shortward of the Lyman limit (912 Å, rest frame) is redshifted into the $u'$ band. Therefore, $z \sim 3$ LBGs are extremely faint ($R \geq 27$) or not detected in this bandpass. Inspection of the $u'$-band images reinforces the non-detection of both components detected in the longer wavelength bands and helps to eliminate low-redshift line-of-sight interlopers.

$^3$Object SDSS J092600.41+442736.1 shows rest-frame H$\alpha$ emission with a separation that is at the limit of what is discernible as two objects in our ground-based survey. It did not receive H$\alpha$ rest-frame UV imaging, so it is unknown at this point whether it has two-component UV flux that would be detectable as a close pair at $z \sim 3$. Strong detection in the rest-frame UV is unlikely because one component is a much redder galaxy that shows an old, or dusty, population in the SDSS spectrum.
UVLG 0808 has a fainter companion ~2 arcsec to the south-east (SE) that exhibits star formation flux in the UV image. An equivalent separation at $z \sim 3$ would be discernible in ground-based images. In addition, the companion has a compact strong detection in the rest-frame Hα image and is the only UVLG in the sample that is detected as two separate galaxies by the Sloan Digital Sky Survey (SDSS).

We search the SDSS spectra of the O08 sample for evidence of double-peak emission in the optical nebular lines. These lines are not subject to outflows as are Lyα emission lines (Section 3.2.1) and should closely trace the systemic velocities. The multiple star-forming regions of seven of the eight systems are located within ~1 arcsec and the component relative velocities are near or below the spectral resolution of SDSS, thus these UVLGs show single-peak emission. However, UVLG 0808 shows evidence of a double-peak feature as witnessed in the Balmer lines. Because the two components of UVLG 0808 have an ~2 arcsec separation, a portion of rest-frame optical flux from the companion galaxy is expected to fall into the SDSS fibre and result in the weaker offset emission line peaks ($\Delta v \sim 280$ km s$^{-1}$). UVLG 0808 is the only object in the sample that (1) has a well-separated companion, (2) appears as two star-forming point source galaxies in the rest-frame UV and (3) shows evidence of double-peak emission in the 1D spectroscopy. Observed at $z \sim 3$, a system with similar properties would appear by our definition as an SSCpair.

Projected component separations of $\geq 4$ h$^{-1}$ kpc are necessary for individual identification of UVLGs in the O08 sample and LBGs in our survey at the resolution of SDSS and LRIS, respectively. The remarkable similarities between the properties of UVLGs at low to intermediate redshift and LBGs at high redshift, and the evidence that interactions provide the bulk of the star formation in UVLGs, leads us to conclude that the separations and emission profiles observed in our SSCpairs likely result from two interacting LBGs. We investigate this further in the following sections and discuss the spectroscopic and morphological properties of LBGs found in the literature.

### 3.2 Spectroscopy

The 2D spectra are individually examined for signs of multiple spectra beyond the usual pipeline reduction of the targeted objects and distinct serendipitous objects. We search for evidence of closely spaced or overlapping spectra, and/or multiple Lyα emission or absorption features. Alongside the image and 2D analysis, we inspect the 1D spectra for evidence of more than one system from redshift fits to ~20 expected interstellar features. The actual number of features fit for a given LBG depends on the redshift and wavelength range probed by the MOS slitlet, and does not include lines that fall near bright night sky emission features which can be difficult to extract cleanly from the faint spectra. The spectra in our sample have continua with relatively low S/N ($\sim 3$–10) and are typical of LBG observations at $z \sim 3$.

Ly$\alpha$ is the most prominent rest-frame UV feature in $z \sim 3$ LBGs and, in contrast, can be detected at a high significance. The LBG spectra compiled to date show roughly 50 per cent of all LBGs dominated by Ly$\alpha$ in emission, with the remaining dominated by Lyγ in absorption (Shapley et al. 2003, and this sample). Net equivalent width (EW) values range from strong emission, $>100$ Å EW, to damped absorption [column densities of N(HI) $\geq 10^{20.3}$ atoms cm$^{-2}$]. Here, we term LBGs that are dominated by Lyγ emission in their spectra, eLBGs, and those dominated by Ly$\alpha$ in absorption, aLBGs. After a thorough search for SSCpairs of all types, we observe that each SSCpair component, with no exception, displays Ly$\alpha$ in emission. Thus, in our nomenclature, all SSCpair components are eLBGs.

The Ly$\alpha$ emission features and continua in the 2D spectra for every SSCpair have the same separations in the spatial direction as the image centroid separation along that same calculated direction. The one-to-one correspondence helps to confirm the distinct two-component nature of the SSCpairs and enables Ly$\alpha$ emission and star-forming continua assignment to each peak in the images. We use the image centroids when correcting the Ly$\alpha$ and interstellar medium (ISM) absorption-line velocity offsets for their angular separation. The separations in the dispersion direction are complicated by the fact that Ly$\alpha$ emission has a large range of velocity offsets with respect to the systemic redshift (see Section 3.2.1). Nevertheless, in the cases where the flux peaks in the images have small separations in the spatial direction, large differences between the offsets of the two Ly$\alpha$ features can provide additional evidence for two major star-forming components.

In practice, detecting double Ly$\alpha$ emission can prove to be easier than double Ly$\alpha$ absorption when component velocity offsets and angular separations are small. Thus, it is possible, that even after a thorough search, we are missing a fraction of LBG spectroscopic close pairs that only exhibit Ly$\alpha$ in absorption because of the low S/N of the spectra and broad nature of the Ly$\alpha$ absorption features. However, LBGs displaying Ly$\alpha$ in absorption typically have stronger ISM transitions that can facilitate the detection of a velocity offset between two overlapping spectra (Shapley et al. 2003; C05). We find no aLBGs at larger radii where both the angular separation and velocity offsets would resolve the Ly$\alpha$ features of the two systems and no clear evidence for double sets of ISM absorption transitions redward of Ly$\alpha$ in aLBG spectra. In addition, we do not find SSCpairs having one component in emission and one in absorption in either the 1D or 2D spectra. Finally, all spectroscopic components of the SSCpair candidates (Figs 1 and 3) show dominant Ly$\alpha$ emission, with none exhibiting dominant Ly$\alpha$ absorption. These findings are discussed further in Section 7. As a result, the observation that all SSCpairs are eLBGs is not primarily a selection effect.

#### 3.2.1 Lyα offsets

We measure corrected Ly$\alpha$ velocity offsets for the SSCpairs of $\Delta v_{Ly\alpha} \sim 400$–1000 km s$^{-1}$. To expand on the difficulties in rest-frame UV continuum interpretation mentioned earlier, Ly$\alpha$ emission in LBGs is observed to be redshifted by $\sim 450 \pm 300$ km s$^{-1}$ with respect to the systemic redshift (C05; Adelberger et al. 2003; Shapley et al. 2003). The velocity offsets likely result from galactic-scale outflows caused by stellar and supernova-driven winds (e.g. Heckman 2002; Adelberger et al. 2003). Ly$\alpha$ photons are absorbed by the approaching outflow while Ly$\alpha$ photons scattered off-resonance from the receding shell can escape. This geometry results in Ly$\alpha$ emission peak velocity offsets that are redshifted with respect to the systemic redshifts and dependent on the host galaxy properties. Consequently, the observed difference between the peaks of the Ly$\alpha$ features cannot be used directly as a measure of the systemic velocity offsets of the SSCpair components.

However, under the following assumption, we can investigate the nature of the component Ly$\alpha$ offsets using the Ly$\alpha$ offset distribution of the LBG population. Because of the one-to-one correspondence between the $\sim 3$–13 h$^{-1}$ kpc projected separations of the flux peaks in the images and the Ly$\alpha$ peaks in the 2D spectra, we attribute
the double-peak Lyα features to two distinct galactic-scale outflows. Admittedly, this is a simplified picture but the relatively coarse resolution of our ground-based observations blends the velocities of any localized regions and can only probe net global outflows.

Adelberger et al. (2003) find a velocity offset distribution between Lyα emission and the ISM absorption lines (Δv_{Lyα−ISM}) of Δv_{Lyα−ISM} = 641 ± 316 km s\(^{-1}\). Because LBG ISM absorption lines are blueshifted on average with respect to the systemic redshift by ≃−150 ± 160 km s\(^{-1}\) (Adelberger et al. 2003; Shapley et al. 2003, and this survey), this results in the above-mentioned 450 ± 300 km s\(^{-1}\) Lyα velocity offset distribution. In addition, Shapley et al. (2003) find that LBGs with dominant Lyα emission (Group 3 and Group 4 in that sample or eLBGs in our nomenclature) show smaller values of Δv_{Lyα−ISM} and therefore evidence of weaker outflows. If we assume that eLBGs have a similar velocity offset distribution in behaviour and form to that of the full LBG population, the eLBG-only distribution becomes Δv_{Lyα−ISM} = 518 ± 266 km s\(^{-1}\), with eLBG Lyα offsets from the systemic redshift of 406 ± 262 km s\(^{-1}\).

If the Lyα emission in the SSCpairs reflects outflow from two star-forming regions in single coalescing systems, we would expect the velocity difference between the two Lyα features, Δv_{Lyα}, to randomly sample either of the above Lyα velocity offset distributions. A random sampling of two values using the distribution of the eLBGs and full LBG population results in expected differences of Δv_{Lyα} = 295 ± 220 km s\(^{-1}\) and Δv_{Lyα} = ∼340 ± 255 km s\(^{-1}\), respectively. However, we find a much larger Δv_{Lyα} = 694 ± 234 km s\(^{-1}\) for the SSCpairs. If we add a line-of-sight velocity component originating from two regions in a bound, massive LBG system by pulling from a Δv_{Lyα−ISM} distribution of relative velocities (e.g. Erb et al. 2003, 2006; Genzel et al. 2008; Law et al. 2009), we find an expected net two-component velocity offset distribution of Δv_{Lyα} ∼320 ± 230 km s\(^{-1}\) (or ∼360 ± 260 km s\(^{-1}\) for the full LBG population), which falls short of describing our data.

The correspondence between the 2D Lyα emission and continua and the two flux peaks in the images forces us to conclude that the Lyα emission features of the SSCpairs arise from either (1) single galaxies, but do not randomly sample the behaviour observed in the full or subset LBG population and that larger than typical Δv_{Lyα} values are correlated with star-forming regions having substantial line-of-sight velocity contributions or (2) star-forming regions with velocity offsets too large to be single systems and are truly pairs of LBGs. In either scenario, the double-peak Lyα emission of the SSCpairs lends insight into the behaviour of z ∼ 3 systems.

3.2.2 ISM absorption

Spectra showing two distinct sets of ISM absorption lines having large velocity offsets together with separate 2D spatial offsets provide strong evidence for two independent systems. We cross-correlate and visually inspect the SSCpairs for ≃20 strong ISM UV transitions that include Lyα, Lyβ, and strong ISM features such as Si ii λ1260, O i/3λλ1302, 1304, C iv λλ1334, 1402, Si textscii1526 and C iv λλ1548, 1550 Å. We find evidence for two systematic redshifts from both the low- and high-ion transitions in the merged 1D spectra. The ISM velocity offsets for the SSCpairs are listed in Table 1. We caution that the low S/N (∼3–10) of the continua and the potentially complex nature of the rest-frame UV behaviour of the ISM, make these the least confident measurements in terms of significance when compared to the other analyses presented here. However, the ISM measurements of the higher S/N low-resolution spectra of 0336−1250 (∼σ) and 1643−2377 (∼11σ) are more secure.

Our data provide tests of the validity of these low S/N measurements. Object 0336−1250 was observed with three separate slitmasks for a total integration time of 11 700 s and the luminous 1643−2377 was observed with three exposures of 1500 s each. In an effort to mimic the lower S/N of the other SSCpair total observations, we performed fits to each of the three 0336−1250 slitmask observations and the individual exposures of 1643−2377 separately. We found agreement to Δz ≤ 0.0015 between the fit to the individual exposures to their respective combined spectrum.

The SSCpairs show a corrected velocity difference between the two identified sets of ISM lines of Δv_{ISM} = 448 ± 109 km s\(^{-1}\). As mentioned above, ISM lines exhibit an ∼150 ± 160 km s\(^{-1}\) range in blueshift from systemic. If we assume that the two sets of ISM lines randomly sample this distribution, we would expect Δv_{ISM} = 180 ± 135 km s\(^{-1}\). If we assume the SSCpairs were single systems with the bulk of the ISM absorption seen in the sightlines to two well-separated star-forming regions with bound relative velocities ≃250 km s\(^{-1}\), we would expect the combined effect to result in Δv_{ISM} ∼ 194 ± 145 km s\(^{-1}\), which is much smaller than the observed value. As a result, the evidence in the ISM lines argue for the SSCpairs to be separate systems.

3.2.3 Lyα–ISM velocity difference

A comparison of the difference between the SSCpair Lyα and ISM features with the relationships found for LBGs is a further test of the viability of the 1D spectral features to help confirm the double-galaxy nature of the SSCpairs. As discussed above, Shapley et al. (2003) determined Δv_{Lyα−ISM} = 614 ± 316 km s\(^{-1}\) for all LBGs and Δv_{Lyα−ISM} = 518 ± 266 km s\(^{-1}\) for eLBGs that are similar to the SSCpairs. Because we see two Lyα emission peaks and evidence for two sets of ISM absorption lines, we treat the SSCpair components as individual systems and measure the Δv_{Lyα−ISM} for each component separately using no angular separation correction. This results in a Δv_{Lyα−ISM} = 475 ± 205 km s\(^{-1}\) when assigning the highest redshift Lyα feature to the highest redshift set of ISM features and the lowest redshift Lyα feature to the lowest redshift ISM features. A re-assignment of the Lyα and ISM features results in the same central value but a larger scatter. The Δv_{Lyα−ISM} distribution found for the SSCpairs agrees with that of the LBG population. Moreover, the distribution follows the trend found in Shapley et al. (2003) for LBGs displaying dominant Lyα emission.

In treating the SSCpairs as close pairs throughout this section, we would expect the 1D spectral features of each galaxy to reflect the relationships and trends of the LBG population. We find that the Δv_{Lyα}, Δv_{ISM} and Δv_{Lyα−ISM} are in good agreement with this picture and are at odds with an interpretation that the SSCpairs represent star-forming regions in single systems.

3.3 Comparison to previous related work

We look for observational precedent in the literature to help interpret the SSCpairs by first exploring the LBG sample of Shapley et al. (2006). This sample consists of deep spectroscopy of 14 LBGs at z ∼ 3 gathered for the purpose of measuring the fraction of escaping continuum flux shortward of the Lyman limit. The observations are valuable for an assessment here because they were selected in the same manner, lay within the same redshift path, and have spectroscopy obtained using the same instrument (LRIS). Moreover, the observations are beneficial here because they have a slightly higher resolution over the bulk of the more relevant wavelengths.
(≤1400 Å rest frame) and have ∼10× longer exposure times for S/N of ∼5–25. In addition, the associated imaging data were obtained with similar or, for the subset of space-based data, superior depth and resolution.

Of the 14 LBGs in that sample, nine are eLBGs. The Lyα EW distribution of the sample is very similar to that of our full spectroscopic LBG sample [Kolmogorov–Smirnov (K–S) test, p = 0.6]. One object, D3, is considered a single system by Shapley et al. (2006) but consists of two galaxies (and separate spectra) with an angular separation of 1.9 arcsec (∼15 h−1 kpc). Three of the nine eLBGs are reported to show double-peak Lyα emission. Because both components of D3 show Lyα emission, merging the two spectra would create a double-peak spectrum, making it a fourth double-peak system (similar to 0957−0941 in our sample). Relevant to later discussion, of the two LBGs shown by Shapley et al. (2006) to exhibit measurable Lyman continuum flux, one is the double-peak Lyα emission system C49 and the other is the pair D3. Narrow-band imaging of D3 shows that it is detected as a Lyα ‘blob’ in the sample of Matsuda et al. (2004) with Lyα emission extending over 17 arcsec2.

We now analyse the double-peak systems of Shapley et al. (2003) as we did for the SSCpairs using the published information. Looking at the velocity offsets of the Lyα feature of the four double-peak systems, we find ΔVLyα = 533 ± 170 km s−1, cf. ΔVLyα = 694 ± 234 km s−1 for our sample. Shapley and coworkers measure one ISM absorption redshift for each of the three Lyα double-peak systems (pair D3 has separate values). If we assign the reported ISM absorption redshifts to the highest redshift Lyα peak, we find ΔVISM−Lyα = 1165 ± 667 km s−1. This places these systems at the high-end tail of the ΔVISM−Lyα distribution for the full LBG population, with one system having the highest (1823 km s−1) velocity difference of the entire z ∼ 3 LBG spectroscopic sample. Assigning the features in this manner implies that it is highly improbable that the double-peak systems are single LBGs.

Instead, if we assign the ISM absorption redshifts to the lowest redshift Lyα peak, we find ΔVISM−Lyα = 579 ± 682 km s−1. While the central value matches the expectations of eLBGs and is in good agreement with LBGs in general, the large scatter of the three systems is unrepresentative of the ± 275 km s−1 scatter that we find for three-galaxy random samples taken from the LBG and eLBG data. In addition, we see similar relative offset and scatter behaviour when we assign the higher redshift ISM features to the lower redshift Lyα emission (and vice-versa) in our SSCpair sample (Section 3.2.3). When inspecting the double-peak system C32, we find the least redshift Lyα peak is blueshifted with respect to the ISM absorption lines by −183 km s−1. If we assign only this system to the higher Lyα peak, then the three systems exhibit ΔVISM−Lyα = 803 ± 322 km s−1 and the scatter is reduced to the level of the expectations. When including the identified pair D3 (ΔVISM−Lyα = 579 km s−1) in the Lyα double-peak sample, we find ΔVISM−Lyα = 713 ± 266 km s−1, which is more consistent with the distribution and scatter of the eLBG and LBG population. Although matching ISM features to one of the Lyα emission peaks can make the double-peak systems fall in line with typical LBGs, what should we make of the second Lyα feature?

The above analysis shows that it is more likely that the three Lyα double-peak LBGs are close pairs similar to D3 and the SSCpair sample as opposed to single systems. Such an interpretation produces a ΔVISM−Lyα distribution in better agreement with the expectations of the LBG population and significantly reduces the scatter. It is possible that the presence of a second set of ISM absorption lines in the Shapley et al. (2006) sample may have been unexpected and ignored, identified and interpreted as strong ISM mixing, or identified and considered of too low significance as a result of blending. Although the S/N of the Shapley et al. (2003) LBG sample is higher than what is typical for z ∼ 3 LBG spectra, it does remain relatively low in that ISM absorption lines remain difficult to study with great confidence. Future investigation of the data (for example, by probing nebular lines in the IR) could resolve this matter.

We remark that Shapley et al. (2003) find 33 per cent (44 per cent depending on slit orientation for D3) of the eLBGs in their sample, and 21 per cent (29 per cent) of the entire sample, to be double-peak systems that meet our SSCpair criteria. The data imply that higher S/N and/or higher resolution should reveal a larger fraction of SSCpairs than that seen serendipitously in our low-S/N, low-resolution survey, with the true fraction potentially even higher.

Next, we examine the study of Law et al. (2007) that consists of space-based imaging of 216 z ∼ 2–3 LBGs and ground-based spectroscopy using LRIS with a similar configuration as our survey. In that work, the morphology of LBGs is quantified using a non-parametric analysis within 1.5 arcsec radius (∼13 kpc) which directly reflects the regime of the SSCpairs. In addition, this is the regime where systems are most sensitive to interaction that can visibly change their morphology and star formation properties. Law and coworkers investigate the rest-frame UV morphology of their LBG sample by quantifying the Gini parameter, colour dispersion, multiplicity and size. The Gini parameter is a measure of the nebulous or nucleated nature of the system, the colour dispersion is measured using V − z broad-band colours and corresponds to rest frame ~1500–2100 Å at z ∼ 3, and the multiplicity parameter quantifies the multiple component nature of the sources.

Law et al. (2007) investigate the relationships between the morphological parameters and the spectroscopic features Lyα EW, low- and high-ionization ISM EW, and ΔVISM−Lyα. As noted in that work, only Lyα EW shows a significant and consistent trend at z ∼ 3 with all four morphological parameters. The Lyα relationships indicate greater Lyα emission EW with decreasing system size, decreasing nebulousity (increasing Gini parameter), decreasing number of nuclei (multiplicity) or nuclei separation and bluer colours. In addition, and in reference to low-redshift UVLAGs, a visual inspection of the space-based images shows that systems with brighter nuclei typically have one or two components whereas systems with fainter nuclei typically have three or more components and are found in more diffuse systems.

Lyα EW is seen to be strongest for large values of the Gini parameter indicating that nucleated sources are more likely to be eLBGs and diffuse sources are more likely to be aLBGs. The Lyα EW increases monototonically over the multiplicity range with values that indicate two strong double nucleated sources (multiplicity parameter value ~10) down to a single nucleated source (multiplicity parameter value 0). Finally, the Lyα EW increases as the size of the systems decrease and the colour becomes bluer. Law et al. (2007) show that each of these trends at z ∼ 3 has a χ2 significance of ≥98 per cent. Taken together, these data can be interpreted to show that double nucleated LBGs exhibit Lyα emission and that the Lyα emission EW increases as the components become bluer and as the separation between the two components decreases, or in other words, as the overall object size becomes progressively smaller for a given multiplicity.

The SSCpair observations are consistent with this behaviour and the interpretation that the SSCpairs are interacting bright double nuclei or two single nuclei LBGs. The double nucleated sources with
larger separations are those discernible as SSCpairs in ground-based data, as also indicated by the work of O08. Diffuse systems, and diffuse systems with multiple fainter clumps, would be observed as single LBGs in ground-based data. Moreover, such systems are LBGs with dominant Lyα absorption from the Law et al. relationships. Strong Lyα EW and blue continuum can be inferred for recent star formation and/or decrease in dust and gas obscuration. The Lyα EW of the SSCpairs in order of decreasing projected separation is 26, 31, 102, 56 and 91 Å. Although the SSCpairs sample is too small to determine a trend, the SSCpairs have similar separations as the double nuclei LBGs in the Law et al. (2007) sample, have blue colours and exhibit Lyα emission with EWs that are in the upper quartile of the full LBG sample.

We comment that the work of Law et al. (2007) does not investigate the behaviour of LBGs with separations larger than ~13 kpc. We probe this regime in Section 4 and address statistics applicable to this discussion in Section 7. In the next section, we test the expectations of finding the SSCpairs by measuring the distribution of LBG close pair separations in our full survey and a larger survey from the literature and by testing ΛCDM predictions using a high-resolution cosmological simulation. We show that the number of SSCpairs are indeed expected and, as a result, the investigation of this and other similar samples offers a unique window into the behaviour and properties of close/interacting high redshift galaxies.

4 SERENDIPITOUS PAIR EXPECTATIONS FROM CLOSE PAIR SEPARATIONS

To investigate the distribution of LBGs on small scales (<500 h^{-1} kpc), we measure the number of LBG pairs versus separation from observation. To help test the universality of the results and to improve the statistics, we augment an investigation of our survey with the photometric and spatial information from the larger survey of S03, consisting of ~2300 colour-selected and ~800 spectroscopically identified LBGs in 17 separate fields.

4.1 Pair definition

For the C05 survey, we consider only LBGs that are identified in our images by SExtractor with m_B ≤ 25.5. The LBGs were selected using u’B’V’R’I’ colour criteria,

\[(u’ - B)_AB > 1.1,\]

\[0.6 < (B - R)_AB < 2.1,\]

\[0.6 < (B - I)_AB < 2.1,\]

\[(u’ - V)_AB > 1.6,\]

\[(V - R)_AB < 0.6,\]

\[(V - I)_AB < 0.6.\]

LBG colour selection at z ∼ 3 is very efficient in filtering out objects not in the redshift path of interest (interlopers). As determined from the two spectroscopic samples, the fraction of interlopers in each survey is similar (~0.20) when considering the particular treatment of the unidentified low S/N spectra. Differences in the photometric selection functions and selection efficiencies between the two surveys are small and are quantified and corrected for using the information from the spectroscopic samples. Figs 6 and 7 present the close pairs versus separation for this survey, the survey of S03, and the combined data set. The two figures emphasize large and small scales, respectively. The fall-off in the number of pairs at radii >10 h^{-1} kpc (best seen in Fig. 7) results from the resolution of the images and the ability for SExtractor to discern close galaxies as separate.

4.2 Pair separations

Overlaid on Figs 6 and 7 are the pair separation expectations from a linear (solid thin red line) and power-law (dotted black line) fit to the raw data. We find that a power-law slope of δ = 0.53 ± 0.01 provides a best fit for all three samples. As illustrated in the two figures, both forms fit well over all separations, with the linear fit showing a departure from the data near, and below, ~30 h^{-1} kpc. Continuations of both fits argue for the existence of LBG pairs with separations smaller than the imaging resolution.

As mentioned above, interlopers comprise a non-negligible fraction of colour-selected LBGs. To estimate the contribution to the pair separations from random interloper line-of-sight projections and to estimate the likelihood that the SSCpairs are random projections, we construct mock catalogues having the physical dimensions of the images. We insert galaxies with random locations in the plane of the sky following the number densities found for each field and the redshift distributions for each survey.

Using catalogues of this design is effective at the small separations studied here because the likelihood of random pairs is low as a result of the relative low surface density of colour-selected galaxies (~1.7 arcmin^{-1}). In addition, the enhancement of the number of random projected close pairs as a result of the spatial clustering of LBGs is negligible as compared to random line-of-sight projections. The z ∼ 3 colour-selection techniques used here probe >500 h^{-1} Mpc. The spatial correlation length of z ∼ 3 LBGs is ~4 h^{-1} Mpc (Adelberger et al. 2003, 2005; C05) with an average of ~1.5 LBGs over random integrated over that volume. Beyond that distance, the clustering effects of LBGs diminishes and the effects of random projections become dominant. Because the projected separations of the SSCpairs are ~15 h^{-1} kpc, the increase in likelihood that the SSCpairs are random projections enhanced by the spatial clustering of LBGs is vanishingly small.

We measure the interloper contribution for each field separately and combine the results from 1000 runs of the mock catalogues. The form of the contamination is shown on Figs 6 and 7 (dashed thin red line) normalized to the total number of separations. From the mock catalogues, we find that the fraction of random projected pairs with separations ~15 h^{-1} kpc averaged over the 26 fields is 0.0002 ± 0.00009. As a result, the SSCpairs are not random projections.

To estimate the interloper contribution to the pair separations, we minimized a \chi^2 fit of a two component distribution that includes the random catalogue results and the angular clustering of LBGs. For LBG angular clustering, we used the conventional form of the angular correlation function, \omega(\theta) = A\theta^{-\delta}. We first test the fit by fixing the slope of the angular correlation function to \delta = 0.57 as found by Adelberger et al. (2005) and varying the fraction of
Figure 6. Histograms of pair separations versus radius. Top panel: number of LBG pairs in our survey binned by $5 \, h^{-1}$ kpc. Overlaid, and more distinguishable on small scales in Fig. 7, is a linear fit (thin solid red line), a power-law fit (thick dotted black line), and the corrected two-point angular correlation function of the form $\omega (\theta) = A\theta^{-0.57}$ (thick solid blue line) fit to the data (see text). The contribution from LBG pairs to the angular correlation function fit is shown by the thick dashed (light blue) line, with the random interloper pairs comprising the remaining contribution. The thin (red) dashed line indicates the form of the random pair contribution normalized to data. As a comparison, the LBG contribution for an angular correlation function with slope $\delta = 0.8$ (thick dot-dashed green line) is shown. Centre and bottom panels: the same as the top panel, but for the survey of S03 and the combined data set from both surveys, respectively.

Figure 7. Same as Fig. 6 but in log/log space to better discern the behaviour on small ($\lesssim 20 \, h^{-1}$ kpc) scales. The photometric close pairs (solid histogram) fail at separations smaller than $\sim 7 \, h^{-1}$ kpc because of the resolution of the images (also see text). The number of close pairs with the addition of the SSCpairs is represented by the dashed histogram. The top panel shows the close pairs and SSCpairs presented in this work. The central panel shows the close pairs for the survey of hereafter S03 and includes predicted SSCpairs using an expected distribution based on the observed distribution found in our survey. The bottom panel shows the combined data sets. These plots illustrate that the predicted SSCpairs fall within the expectations of all functional fits at small radii and that the probability that the SSCpairs are the result of random pairings is extremely low.
interlopers, $f_i$. We find the best fit when using an interloper fraction of $f_i = 0.196$ and 0.195 for the C05 and S03 samples, respectively. The contribution by the LBG angular correlation function is shown in Figs 6 and 7 as the thick dashed (light blue) lines with the combined two-component LBG/random contribution (corrected angular correlation function) shown by the thick solid (blue) lines. To help illustrate the effect, the slope of the angular correlation function has on the results, we also show the LBG contribution when using a slope of $\delta = 0.8$ (dashed green line).

We re-fit the data letting both parameters vary freely and found best fits in $\delta$ and $f_i$ within ~3 per cent of the above values. Because this type of test has a small dependence on choice of bin size, we use the fixed $\delta = 0.57$ (Adelberger et al. 2005) result in our assessment of SSCPairs expectations. The consistency in pair distributions and parameter fits for both surveys illustrates the utility of using pair separations to describe the behaviour of LBGs on small scales.

The number of LBG close pairs predicted by the corrected angular correlation function provides a good match to the observed pairs on all scales down to the resolution of the images and becomes indistinguishable from the uncorrected LBG angular correlation function expectations at separations smaller than $\sim 30 h^{-1}$ kpc. This agreement reiterates the negligible contribution of random projected pairs on small scales.

The widths of our spectroscopic slitlets are $\lesssim 8 h^{-1}$ kpc. Inspecting Fig. 7 at separations of $\lesssim 15 h^{-1}$ kpc shows that the expectation from every functional fit to the data predicts that we should find close pairs serendipitously in our slitlets. From the fit of the corrected (and uncorrected) LBG angular correlation function, we find that both the expected number of SSCPairs and the expected distribution of SSCPair separations agree well with that of the observations (shown as the dashed histogram in Fig. 7).

### 5 SERENDIPITOUS PAIR EXPECTATIONS FROM SIMULATION

We test the identification of the SSCPairs against the predictions of ΛCDM by analysing a high-resolution hybrid numerical/analytical cosmological simulation (Berrier et al. 2006). The full description of the simulation and the close pair analysis is presented in a companion paper, Berrier et al. (in preparation). Below we describe a few of the relevant specifics and results.

For large-scale structure, the simulation uses an adaptive refinement tree $N$-body code (Kravtsov, Klypin & Khokhlov 1997) that follows the evolution of 512$^3$ particles in a comoving box $120 h^{-1}$ Mpc on a side. Numerical overmerging on small scales is overcome by incorporating the analytic method of Zentner et al. (2005) to trace the substructure. We sample the simulation at the $z = 3$ time-step and use dark matter haloes in the simulation that match the spatial correlation function of the form $\xi(r) = (r/r_0)^{-\gamma}$ measured for the $m_r \leq 25.5$ LBG samples. We adopt the spatial correlation length $r_0 = 3.3 \pm 0.6$ (Cooke et al. 2006) using a fixed slope $\gamma = 1.64$ for the C05 survey and $r_0 = 4.0 \pm 0.6$ and $\gamma = 1.57 \pm 0.14$ (Adelberger et al. 2005) for the S03 survey. We find that haloes with $v_{\text{esc}} \geq 140 \text{ km s}^{-1}$ in the simulation yield a correlation length of $r_0 = 3.9 \pm 1.5$ and slope of $\gamma = 1.6 \pm 0.3$. These haloes correspond to a number density of $n_{\text{halo}} = 0.016 h^3 \text{ Mpc}^{-3}$, comoving, and halo mass $M_{\text{halo}} > 10^{11.3} M_\odot / (M_{\text{halo}}) \sim 10^{11.8} M_\odot$ which are in very good agreement with the corrected volumetric density from the photometric sample and the mass inferred from clustering statistics ($\sim 10^{11.5} M_\odot$, Adelberger et al. 2003, 2005; Cooke et al. 2006).

The simulation is then analysed in a manner identical to the observations using (1) the constraints from the seeing FWHM and centroid accuracy from the images, (2) the MOS spectroscopic slitlet dimensions of our survey, (3) the spectral resolution and (4) the uncertainties in determining the systemic LBG spectroscopic redshifts. We compute the number of pairs that fall in mock slitlets with random orientations that are resolvable in the images and that have velocity offsets that would be detectable in LRIS spectroscopy. We find an expected fraction of $0.052 \pm 0.002$ or an average of 7.1 LBGs (3–4 pairs) that is to be compared to the $0.069 \pm 0.023$ fraction found from the analysis of this survey. This close agreement helps reinforce the interpretation that the SSCPairs are indeed close $z \sim 3$ LBG pairs as a similar number are expected from ΛCDM to be found serendipitously in our survey. We find that the expected fraction of SSCPairs from the simulation is rather insensitive (changes by a few percent) to a variation of the LBG correlation parameters within the range of their uncertainties.

### 6 SERENDIPITOUS Lyα EMITTERS

LAEs are defined here as objects displaying detectable Lyα emission but have continua fainter than $R = 25.5$ and therefore are not candidates for inclusion in the LBG spectroscopic sample. We discovered two serendipitous $z \sim 3$ LAEs in the MOS slitlets of the full C05 LBG sample. This is approximately the number we would expect to fall serendipitously into our slitlets, when we consider (1) the depth of our spectroscopy, (2) the $\sim 1 \text{ arcmin}^2$ solid angle subtended by our slitlets and (3) the $z \sim 3$ LAE densities reported by Gawiser et al. (2007) and Grove et al. (2009) when assumed to be constant over the redshift path probed. The detected objects are LAE-228 at $z = 3.007$ in field PC1643+4631A and LAE-475 at $z = 3.209$ in the field BR11013+0035. Fig. 8 presents their 1D and 2D spectra. Both redshifts are measured from their Lyα emission peaks and exhibit Lyα EW of 48 and 140 Å, respectively.

Interestingly, LAE-228 was found as a spectroscopic close pair to the spectroscopically confirmed LBG-228 with $z = 3.008$. The projected separation between the two systems is $22.7 \text{ kpc}$ and they exhibit $\Delta v_{\text{sep}} = 450 \text{ km s}^{-1}$. In addition, LAE-475 was found near LBG-475 with $z = 3.218$ having a projected separation of $40.1 \text{ kpc}$ and a Lyα velocity offset of $650 \text{ km s}^{-1}$. Although both systems could be considered close pairs, neither is included in the analysis in this paper because the LAEs do not meet the $m_r \geq 25.5$ criterion and because LBG-475 is considered a 'probable' LBG (category 4 in Cooke et al. 2006) from the lower S/N and quality of the spectral-line fit.

LAEs are believed to be systems with lower mass and lower star formation rates than that of the LBG population ($\sim 10^{10.5–11} M_\odot$ and $\lesssim 10 M_\odot \text{ yr}^{-1}$; e.g., Gawiser et al. 2007) that are undergoing a recent star-forming episode. The fact that the two LAEs detected are close pairs to one, and likely both, LBGs suggests that a fraction of the Lyα emission, and therefore the detectability of LAEs, may result from interactions.
Finally, LBG-228 with close pair LAE-228 (22.7 kpc separation) shows weak evidence of complex Lyα profiles. In the probability calculations below, we use the eLBG fraction from our survey exclusively. The eLBG fraction found by Shapley et al. (2003) analysis of the S03 data would result in lower probabilities.

The binomial probability of observing all 10 SSCpair galaxies with dominant Lyα emission and zero galaxies with dominant Lyα in absorption by chance is $p \approx 0.0025$. The six spectroscopic LBG candidates of the SSCpair candidates all show dominant Lyα in emission and were not included in the SSCpairs analysis because the bulk of the secondary component did not enter the slitlet (Figs 1 and 3). Combined, the binomial probability that all 16 galaxies are eLBGs and zero are aLBGs is $p = 7.0 \times 10^{-5}$. If the emission of these systems was a result of star-forming clumps or single LBGs, we would expect to observe an approximately equal fraction (or ~45% per cent for this survey) of regions that are dominated by Lyα absorption and we observe none. As a reminder, systems exhibiting Lyα absorption (aLBGs) were searched for thoroughly in the data (Section 3.2).

When examining the Lyα features of spectroscopic LBGs having photometric companions that meet our colour criteria and have projected separations between 15–50 $h^{-1}$ kpc, with the caveat that some of these may not be physical pairs, we find 11 eLBGs and 7 aLBGs ($p = 0.17$). In addition, if we include all spectroscopically confirmed LBGs with photometric close pairs that have relaxed colour criteria (see C05) and that have projected separations between 15 and 50 $h^{-1}$ kpc (those with $<15$ $h^{-1}$ kpc are included in the SSCpair candidates), we find a total of 15 eLBGs and eight aLBGs ($p = 0.11$). These two measurements suggest an overabundance of eLBGs and, combined with the abundance of Lyα emission in the SSCpairs and SSCpair candidates, indicate an overabundance that diminishes with increasing radius. Fig. 9 plots the number of eLBGs and aLBGs with photometric companions with separation. Finally, LBG-228 with close pair LAE-228 (22.7 $h^{-1}$ kpc) exhibits Lyα emission. The tentative LBG-475 with close pair LAE-475 (40.1 $h^{-1}$ kpc) shows weak evidence of complex Lyα absorption and emission in the low S/N spectrum, but a proper EW analysis is not possible at this time.

We posit that the overabundance of eLBGs at small separations ($\lesssim 15$ $h^{-1}$ kpc) is caused, in part, by induced star formation and the dispersal of gas and dust related interactions. Object D3 in the sample of Shapley et al. (2003) provides further support in that both galaxies in the identified close pair ($\sim 15$ $h^{-1}$ kpc separation) exhibit dominant Lyα emission. The extended Lyα emission of D3, Lyα

**Figure 8.** Spectra of the LAEs and close LBGs detected in the survey. Top split panel: 1D spectra of LBG-228 and LAE-228 showing the Lyα emission and continua of both objects. Centre split panel: 1D spectra of LBG-475 and LAE-475. LAE-475 shows strong Lyα emission, however, LBG-475 is considered a probable LBG because of the low S/N and inconclusive nature of the ISM line fit. Bottom two panels: the 2D spectra for pairs 228 and 475. The position of the Lyα features and continua for pair 228 and 475 are indicated and have projected separations of 22.7 and 40.1 $h^{-1}$ kpc, respectively. Although both pairs are within the close pair separation criteria, they are not included in the analysis because the LAEs do not meet the $m_R < 25.5$ criterion and LBG-475 has too low S/N.
blob nature, and potential fraction of escaping Lyman continuum photons reinforces this scenario. Finally, the trends of Lyα emission with morphological parameters are consistent with a picture where a non-negligible fraction of LBGs produce double-peak Lyα emission when merging their ground-based 1D spectra as a result of triggered or more revealed Lyα emission.

The statistics presented here can be quickly improved from the analysis of other similar existing and future data sets. Nevertheless, the Lyα behaviour of the SSCpairs appears real. Such behaviour would suggest that although star formation is ubiquitous at high redshift, caused in part by the high gas fraction in most systems, and generates Lyα emission, close pairs have additional Lyα emission and UV flux as a result of an interaction. The enhanced Lyα emission from interactions modifies the ratio of eLBGs and increases the fraction of detectable eLBGs for a given criteria whereas without an interaction they would remain either too faint or too red. Such behaviour would bias any colour-selection technique. Similarly, interactions may make LAEs detectable whereas without an interaction they would remain too faint to be detected from their continuum alone.

We find ~7 per cent of the galaxies in our spectroscopic sample identified as interacting pairs. If the higher fraction of Lyα double-peak systems in the higher S/N and higher resolution sample of Shapley et al. (2006) prove to be interacting pairs, because both samples are serendipitous detections, the true fraction of interacting LBGs at \( z \approx 3 \) may be \( \geq 30 \) per cent. If borne out, the double-

![Figure 9. Histograms of the Lyα behaviour of spectroscopic LBGs with close photometric companions. Pair separations where the spectroscopic component exhibits dominant Lyα absorption indicated by the red (grey) back-hatched histogram (upper panel) and dominant Lyα emission are indicated by the blue (black) forward-hatched histogram (lower panel). The SSCpairs are not included. All SSCpair components have separations of \( <15 h^{-1} \text{kpc} \) and show Lyα emission. Pairs shown with \( <15 h^{-1} \text{kpc} \) separations include the SSCpair candidates.](image)

8 SUMMARY

A systematic search of deep Keck imaging and spectroscopy of \( 140z \approx 3 \) LBGs in nine separate fields has uncovered five serendipitous spectroscopic close pairs (SSCpairs) with separations of \( <15 h^{-1} \text{kpc} \). Below, we summarize our findings and the implications of the imaging and spectroscopic data from this survey, the photometric data from the survey of S03, and the results from an analysis of a carefully matched high-resolution cosmological hybrid simulation.

(i) We find evidence in the imaging and spectroscopic observations that the SSCpairs are two distinct and likely interacting systems.

(ii) Each component of the SSCpairs exhibits detectable Lyα emission and a corresponding 2D continuum. The continua of the SSCpairs are closely spaced or overlapping. When merging the 1D spectra, each SSCpair shows a double-peak Lyα emission profile which is therefore different in nature than those modelled for a static or expanding shell of gas driven by galactic-scale outflows. The Lyα emission peaks and continua in the 2D spectra are spatially offset and exhibit a one-to-one spatial correspondence with continuum flux peaks in the images.

(iii) The velocity offsets between the two Lyα emission peaks of the SSCpairs (before and after angular separation corrections) are not representative of a random sampling of Lyα offsets pulled from the LBG population if the two features are generated by
two sources within single systems. Instead, the Lyα offsets are in agreement with single Lyα emission from two separate systems.

(iv) We see evidence for two sets of ISM absorption lines (at a lower confidence level) in each merged SSCpairs spectrum having relative velocities inconsistent with the expectations of the general LBG population but consistent with two separate systems. In addition, the velocity differences between the Lyα and ISM features assigned to each component of the SSCpairs, under the assumption that they are distinct systems, are consistent with typical LBG values.

(v) The high-S/N, higher resolution $z \sim 3$ LBG spectroscopic sample of Shapley et al. (2006) report that four of the nine eLBGs in their sample of 14 systems display double-peak Lyα emission. Analysis of the reported values finds the data for the three double-peak systems and one identified double system to be consistent with the SSCpairs observations. Both samples show Lyα and potential ISM offsets and Lyα–ISM velocity differences that are less consistent with a single system and more consistent with typical values for two interacting $z \sim 3$ galaxies.

(vi) The morphology and Lyα features of the SSCpairs are consistent with the reported relationships of Law et al. (2007) between space-based morphological parameters (Gini, multiplicity, size and colour) and Lyα emission EW of $z \sim 3$ LBGs. An interpretation of the these relationships points to a picture where single and double-nuclei LBGs are Lyα emitting LBGs, with a significant fraction being interacting systems.

(2) We examine the distribution of all close pairs in the data to determine the expectation of serendipitous pairs in our spectroscopic slitlets. We find that an angular correlation function of the form $\omega(\theta) = A \theta^{-3}$ with slope $\delta = 0.57$ provides an excellent fit to close pair counts for both surveys tested. The fit incorporates contamination by random interlopers determined from mock catalogues matched to the volume and behaviour of the data. The slope of the fit to the close pair counts is identical to, or in very close agreement with, the $z \sim 3$ LBG values in the literature derived from angular and spatial clustering statistics. Extrapolation of the fit to below the resolution limit of the photometric data ($\lesssim 10 h^{-1} \text{kpc}$) predicts the existence of SSCpairs with a similar number and separation distribution to that observed.

(3) We analyse a high-resolution cosmological hybrid numerical and analytical simulation to assess the expectation of the SSCpairs from the predictions of $\Lambda$CDM. We carefully matched the simulation to the number density, spatial correlation function, spectral and imaging resolutions of the data, and the dimensions of the slitlets. The analysis finds a prediction of $\sim 4$ pairs to fall serendipitously in the multi-object slitlets of our survey, in good agreement with the observations.

(4) We present two LAEs discovered serendipitously in the MOS spectroscopic slitlets which are expected from LAE densities at $z \sim 3$ and the solid angle subtended by our slitlets. However, both LAEs are $\lesssim 50 h^{-1} \text{kpc}$ close projected pairs to LBGs. We confirm one of the LAEs to lay at the redshift of a nearby LBG and is a bona fide close pair ($22.7 h^{-1} \text{kpc}$), whereas the second is only a probable close pair because of the low S/N of the LBG spectrum. In addition, the LBG in the bona-fide close pair exhibits Lyα emission.

(5) We uncover a relationship between Lyα emission and pair separation. We find an overabundance of LBGs with separations of $< 50 h^{-1} \text{kpc}$ exhibiting Lyα emission as compared to the full sample. Moreover, without exception, all galaxies in the SSCpairs and all SSCpair candidates ($\lesssim 15 h^{-1} \text{kpc}$) have dominant Lyα emission.

The presence of Lyα in all SSCpairs and SSCpairs candidates supports the interpretation that the SSCpairs are interacting LBGs under the assumption that interaction may disperse gas and dust and trigger observable star formation. Because of the close proximity of the galaxies in the data to each other, the double Lyα emission/double morphology of the SSCpairs provides a useful and consistent diagnostic to help detect interacting close pairs from $2 \lesssim z \lesssim 7$ in similarly obtained existing and future optical ground-based data.

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