Lyman-break galaxies at $z \sim 5$ – I. First significant stellar mass assembly in galaxies that are not simply $z \sim 3$ LBGs at higher redshift

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Accepted 2006 December 29. Received 2006 December 7; in original form 2006 October 3

ABSTRACT
We determine the ensemble properties of $z \sim 5$ Lyman-break galaxies (LBGs) selected as V-band dropouts to $i_{\text{AB}} < 26.3$ in the Chandra Deep Field–South using their rest-frame UV-to-visible spectral energy distributions. By matching the selection and performing the same analysis that has been used for $z \sim 3$ samples, we show clear differences in the ensemble properties of two samples of LBGs which are separated by 1 Gyr in look-back time. We find that $z \sim 5$ LBGs are typically much younger ($<100$ Myr) and have lower stellar masses ($\sim 10^9 M_\odot$) than their $z \sim 3$ counterparts (which are typically $\sim$ few $\times 10^{10} M_\odot$ and $\sim 320$ Myr old). The difference in mass is significant even when considering the presence of an older, underlying population in both samples. Such young and moderately massive systems dominate the luminous $z \sim 5$ LBG population ($\gtrsim 70$ per cent), whereas they comprise $\lesssim 30$ per cent of LBG samples at $z \sim 3$. This result, which we demonstrate is robust under all reasonable modelling assumptions, shows a clear change in the properties of the luminous LBGs between $z \sim 5$ and $z \sim 3$. These young and moderately massive $z \sim 5$ LBGs appear to be experiencing their first (few) generations of large-scale star formation and are accumulating their first significant stellar mass. Their dominance in luminous LBG samples suggests that $z \sim 5$ witnesses a period of widespread, recent galaxy formation. As such, $z \sim 5$ LBGs are the likely progenitors of the spheroidal components of present-day massive galaxies. This is supported by their high stellar mass surface densities, and is consistent with their core phase-space densities, as well as the ages of stars in the bulge of our Galaxy and other massive systems. With implied formation redshifts of $z \sim 6–7$, these luminous $z \sim 5$ LBGs could have only contributed to the UV photon budget at the end of reionization. However, their high star formation rates per unit area suggest these systems host outflows or winds that enrich the intragalactic and intergalactic media with metals, as has been established for $z \sim 3$ LBGs. Their estimated young ages are consistent with inefficient metal-mixing on galaxy-wide scales. Therefore these galaxies may contain a significant fraction of Population III stars as proposed for $z \sim 3$ LBGs by Jimenez & Haimann.

Key words: galaxies: evolution – galaxies: formation – galaxies: high-redshift – galaxies: starburst.

1 INTRODUCTION
One of the fundamental open questions in cosmology is when did galaxies form their first generations of stars? Identifying and study-

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ing such galaxies are key steps towards understanding the physical processes that drive galaxy formation. Probing the formation and early growth of systems similar to the Milky Way requires observations of galaxies when the Universe is still young. Specifically, theoretical calculations (Mo & White 2002) predict that the most rapid growth of galaxies with masses comparable to that of the Milky Way occurs at redshifts of approximately $z \sim 5$. This is not long after the end of the (complex) reionization process, which recent three-year Wilkinson Microwave Anisotropy Probe results indicate was underway at $z \sim 11$ (Alvarez et al. 2006) and was largely
complete by redshifts $z \sim 6–6.5$ (Becker et al. 2001; Fan et al. 2001; Malhotra & Rhoads 2004; Fan et al. 2006). Estimates of the ionizing photon density in the early Universe suggests that the UV emission from currently known high-redshift galaxies, whether star formation or AGN dominated, is insufficient to have caused reionization. However, these galaxies must have had an impact on the intergalactic medium (IGM) at high redshift. Only through comprehensive studies of the physical properties [including masses, star formation rates and histories (SFRs and SFHs, respectively), and clustering strength] of galaxies that were in place at this epoch, can we accurately assess their contribution to the mass growth of galaxies like our own, and their effect on the gaseous IGM at the end of reionization.

As part of an ongoing study of high-redshift galaxies, we have investigated the rest-frame UV-visible properties of candidate Lyman-break galaxies (LBGs) at $4.6 \lesssim z \lesssim 6$ selected as V-dropouts using the now standard Lyman-break technique (Steidel & Hamilton 1993; Steidel, Pettini & Hamilton 1995; Steidel et al. 1999). Through spectroscopic confirmation, we have successfully demonstrated the efficacy of this technique for unambiguously identifying $z \sim 5$ galaxies from deep imaging surveys in the rest-frame UV using 8-m class telescopes (Lehnert & Bremer 2003). From these data it has been possible to determine the comoving density of high-redshift LBGs (Bunker et al. 2004), their likely contribution to the end of reionization (Lehnert & Bremer 2003), and the fraction of sources which host supermassive black holes (Bremer et al. 2004). However, the rest-frame UV data alone are thus far insufficient to accurately constrain the ages, dust content, SFRs and masses of the LBG population at high redshift.

Rather, accurately constraining these parameters relies on well-measured rest-frame UV-to-visible spectral energy distributions (SEDs). At $z \sim 5$, the rest-frame UV emission from ongoing star formation is redshifted into the observed visible, while emission in the rest-frame visible to near-infrared from older stars, diagnostic of longer or earlier periods of star formation, shifts into the mid-infrared. Several fields now have excellent multiwavelength data sets from both the Hubble and Spitzer Space Telescopes (HST and Spitzer, respectively) supplemented by ground-based data sets, and form an ideal basis for selecting and studying samples of distant galaxies across the full rest-frame UV to visible wavelength range.

The most detailed multiwavelength studies to date of $5 < z < 7$ LBGs have been centred upon a small fraction of dropouts that benefit from amplification due to lensing and/or those detected with Spitzer-IRAC (Chary, Stern & Eisenhardt 2005; Dow-Hygeland et al. 2005; Egami et al. 2005; Eyles et al. 2005; Mobasher et al. 2005; Schaerer & Pelló 2005; Yan et al. 2005, 2006a). Since, at $z > 5$, the Balmer break lies between the $K_s$ and the IRAC passbands, the IRAC data are highly effective in constraining the ages of these systems. A strong detection with IRAC normally confirms the presence of a Balmer break or an intrinsically more UV luminous system. The derived properties of these high-redshift LBGs are fascinating; massive (few-several $\times 10^{10} M_\odot$) and strongly star-forming systems with ages comparable to the age of the Universe at that epoch. The presence of such massive and evolved systems at high redshift, in place less than a billion years after the big bang, challenges the expectations from bottom-up hierarchical structure formation scenarios (however, also see McLure et al. 2006).

These derived masses and ages of $z \gtrsim 5$ LBGs are similar to the average properties of LBGs at redshift 3. Following the pioneering work of Steidel et al., the last decade has seen intensive observational and theoretical studies on the properties of LBGs at $z \sim 3$, providing a wealth of information about this abundant population of UV-bright galaxies at this epoch. These star formation dominated systems are seen to host strong outflows (Pettini et al. 2001; Adelberger et al. 2003; Shapley et al. 2003), typically have subsolar-to-solar metallicities ($\sim 0.3–1 Z_\odot$; Pettini et al. 2001; Shapley et al. 2003) and possibly contain a significant component of Population III stars (Jimenez & Haiman 2006). LBGs are shown to be highly clustered on both large and small scales, the latter being indicative of common halo objects (Adelberger et al. 1998; Giavalisco et al. 1998; Ouchi et al. 2004b, 2005; Lee et al. 2006). Recent follow-up of $z \sim 3$ LBGs with Spitzer has revealed a division in the population between LBGs with significant dust-attenuated star-forming regions as well as the UV-emitting ones (Huang et al. 2005). This division is also seen for LBGs at $z \sim 1$ (Burgarella et al. 2006) with 40 per cent being infrared bright. Recently Reddy et al. (2005) have reported on the potential relation between UV- and infrared-selected populations. Huang et al. (2005) suggest infrared-luminous LBGs are the missing link between LBGs and submillimetre galaxies and are the progenitors of present-day giant ellipticals (see also Adelberger & Steidel 2000; Shu, Mao & Mo 2001; Ouchi et al. 2004b; Rigopoulou et al. 2006).

But how do these properties compare to those samples of LBGs at higher redshifts? Do we see an evolution in the properties of similar LBGs at these two epochs? Because of the small number of sources investigated, and the inhomogeneity of the selection criteria used, it has not yet been possible to consistently compare the derived properties of $z \gtrsim 5$ LBGs directly with those of LBGs at $z \sim 3$. In a preliminary study, Ando et al. (2004) find that unlike $z \sim 3$ LBGs (Shapley et al. 2003) the majority of luminous $z \sim 5–6$ LBGs have weak or absent Lyα emission and strong low-ionization absorption lines, already indicating key differences between the populations at redshifts 5 and 3. We complement this comparison by analysing the properties of a large and reliable sample of the most luminous LBGs ($L > L^*$) at $z \sim 5$ which match the luminosity to which LBGs at redshift 3, $\sim 1$ Gyr later. This difference is longer than the typical duration of the UV luminous phase of a $z \sim 3$ LBG, thus we are not comparing the same galaxies, but galaxies at two epochs with similar UV-emission characteristics.

To address these issues, we present the results from an analysis of the properties of a sample of luminous V-band dropouts selected from the multiwavelength data sets of the Chandra Deep Field-South (CDF-S; Giacconi et al. 2001). This field was chosen as the southern field of the Great Observatories Origins Deep Survey (GOODS; Dickinson et al. 2003a), for which public imaging data are available over 10 bands covering the visible [HST-Advanced Camera for Surveys (ACS)], near-infrared (VLT-ISAAC) and mid-infrared (Spitzer-IRAC) wavelength ranges. In Section 2 we describe our methodology and selection criteria that define this robust sample of $z \sim 5$ LBGs. The stellar evolutionary modelling is discussed in Section 3. The resultant physical properties of mass, ages, SFR and extinction of the galaxies in this sample are detailed in Section 4 and the comparison to the properties of $z \sim 3$ galaxies is presented in Section 5. Unlike similarly luminous $z \sim 3$ LBGs, and other $z > 5$ LBG samples, we find our sample to be dominated by young ($< 100$ Myr) and moderately massive ($\sim 10^9 M_\odot$) galaxies. We discuss the implications of our findings in Section 6.

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1 We explore how different assumptions in the modelling process affect the results of our analysis in Appendix A and the potential contribution from an underlying old population in Appendix B.
We adopt the following flat cosmology throughout this paper: $H_0 = 70 \text{km s}^{-1} \text{Mpc}^{-1}$, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$. All magnitudes are based on the AB magnitude system (Oke & Gunn 1983).

2 DATA AND SAMPLE SELECTION

2.1 Selection criteria

We applied a Lyman-break colour selection to the publicly available HST/ACS imaging data sets of the CDF-S obtained through the filters F435W ($B$), F606W ($V$), F775W ($i$) and F850LP ($z$) (Giavalisco et al. 2004b). Specifically, we selected objects with $V_{\text{AB}} - i_{\text{AB}} > 1.7$ mag which were not detected (signal-to-noise ratio <3) in the F435W ($B$-band) image (i.e. shortward of the 912 Å Lyman break at $z \sim 5$) ensuring that we only selected sources with a clear Lyman discontinuity in their emission. We then required that the objects were reliably detected (signal-to-noise ratio >5 in the $z$-band) in order to accurately measure the sizes of the UV emitting regions. Furthermore, as mentioned above, we matched our sample to the magnitude limit to which LBGs at $z \sim 3$ have been spectroscopically confirmed. This limit of $R_{\text{AB}} \sim 25.5$ probes $z \sim 3$ LBGs brighter than $\sim 0.4 L^*$ (Steidel et al. 2003). At $z \sim 5$, $R_{\text{AB}} \sim 25.5$ corresponds to $i_{\text{AB}} \sim 26.3$ mag, the magnitude to which we select our sample of $z \sim 5$ LBGs. This colour selection is similar to those previously used to select $V$-band dropouts (or the analogous $R$-band dropouts in young, $\sim 10$ Myr, $z_{\text{ph}}=4.64$)

(iii) young $\sim 50$ Myr, $z_{\text{ph}}=4.44$

(iv) young $\sim 50$ Myr, $z_{\text{sp}}=4.9$

(v) intermediate $\sim 150$ Myr, $z_{\text{ph}}=4.84$

(vi) old $\sim 700$ Myr, $z_{\text{ph}}=4.5$

(vii) low-$z$ interloper, $z_{\text{ph}}=1.82$

Figure 1. (i) This figure shows $5 \times 5$-arcsec$^2$ images of a typical galaxy from our sample in the 10 filter bands we consider. Six SEDs are shown in panels (ii–vii). The best-fitting model is plotted over the data points. Panels (ii–vi) show SEDs for five galaxies from our robust sample of $z \sim 5$ LBGs. The SEDs are arranged (from left- to right-hand side and then down) in approximate best-fitting age order showing the emergence of the Balmer break between the $K_s$- and 3.6-μm data points. The SED of a low-redshift interloper is shown in panel vii for comparison. Panels iii, iv and vi are spectroscopically confirmed $z \sim 5$ LBGs.

Lehnert & Bremer 2003, but see also Stark et al. 2006 and Vanzella et al. 2006 for a discussion of alternative colour cuts), which have been successfully spectroscopically confirmed to lie at $z \sim 5$ (Giavalisco et al. 2004a; Yan et al. 2005; Vanzella et al. 2006).

2.2 Input data

For each object we combined the ACS data with publicly available near- and mid-infrared data sets to construct multiwavelength SEDs covering 0.45 to 8 μm (Fig. 1). The ground-based $J$- and $K_s$-band data were taken with ISAAC at the Very Large Telescope (VLT) (Olsen et al. 2006, and http://www.eso.org/science/goods/imaging/products.html), and the mid-infrared data with Spitzer/IRAC at 3.6, 4.5, 5.6 and 8.0 μm (Dickinson et al., in preparation and http://data.spitzer.caltech.edu/popular/goods/, see also brief descriptions in Yan et al. 2004 and Stark et al. 2006).

While we used the publicly available reduced images for the ACS and ISAAC data, we performed post-pipeline processing on the GOODS-S/Spitzer data (from epochs 1 and 2) creating deep $1 \times 1$-arcmin$^2$ mosaics centred on each high-redshift candidate using the Spitzer/MOPEX package. The resultant drizzled mosaics have had instrumental effects and cosmic ray events removed. The mosaics were registered to the ACS astrometric reference frame using common detections to an accuracy of $\sim0.1$ arcsec. We verified our IRAC mosaic generation and photometric calibration by
performing the same procedure to extract photometry for A and F stars identified in the field (Groenewegen et al. 2002). Such stars rarely show an infrared excess or have strong absorption features in the mid-infrared, thereby enabling accurate predictions of their mid-infrared emission. The fluxes predicted by blackbody fits to the templates of their spectral types were reproduced to within 0.1, 0.1, 0.2 and 0.3 mag of our aperture photometry at 3.6, 4.5, 5.8 and 8 μm, respectively, consistent with our adopted accuracies (see later for a description of our adopted photometric uncertainties). Additionally, we confirmed that our measured fluxes were consistent with those measured for our LBG candidates and the stars from the epoch 1 and 2 GOODS Enhanced Legacy products (Dickinson et al., and http://data.spitzer.caltech.edu/popular/goods/).

The deep GOODS/IRAC data have the largest spatial pixels and point spread functions (PSFs) amongst our data sets and, as a result, in crowded regions the emission profile from a given source can overlap with those of adjacent sources. For those sources selected according to the above criteria, but blended with neighbours in the Spitzer data, we treated the mid-infrared IRAC fluxes as upper limits in the subsequent SED analysis.

For each source that satisfied our Lyman-break criteria, we built a 10-band SED with fixed diameter aperture photometry performed on each image (see Fig. 1). Apertures, appropriate for the characteristics of each image, were determined based on enclosing as large a fraction of the source flux as possible while minimizing the impact of the sky background noise and flux contributions from neighbouring sources. We used apertures with diameters of 1, 2 and 4.5 arcsec for the measurements on the ACS, ISAAC and IRAC images, respectively. Small aperture correction factors were applied to account for the fraction of the total flux not enclosed by our fixed-diameter apertures: 1.07 for the four ACS bands, 1.10 for the two ISAAC bands, 1.18 for the IRAC 3.6- and 4.5-μm bands, and 1.35 and 1.47 for the 5.8- and 8-μm bands. We determined the aperture corrections based on the PSF of each mosaic, constructed from isolated, bright but unsaturated stars throughout the CDF-S and taking reference to the CDF-N. As the pixel-to-pixel rms assuming uncorrelated Gaussian noise statistics. The simulations were performed for a range of aperture diameters. As a function of linear aperture size N, the empirically derived relationship shows that the photometric uncertainties lie above and grow faster with size than the σ ∝ N dependence for pure Gaussian noise. However, for a given aperture size, the histogram of background fluxes is very well described by a Gaussian distribution (of which the dispersion is taken as the 1σ uncertainty for photometric measurements in the given aperture size).

A conservative absolute calibration uncertainty of 10 per cent was additionally included in the final adopted uncertainty to comfortably account for the relative uncertainties in photometric calibration across the 10 bands. In our SED modelling, this additional uncertainty prevents the fits being driven by a few photometric points with very small errors. We note that adopting a less conservative value for this uncertainty would mainly act to reduce the range of acceptable older ages, which is most influenced by the IRAC photometry, and therefore would not alter our findings of young ages for the majority of our sources.

2.3 Defining a robust sample of z ~ 5 Lyman-break galaxies

Our initial rest-frame UV selection yielded a sample of 109 z ~ 5 LBG candidates. This sample will include a fraction of spurious sources that are not LBGs (low-redshift galaxies, quasars and stars) and also some sources with insufficient photometric constraints (regardless of their nature) to reliably determine their properties. We have therefore culled the initial sample as follows.

Assisted by SEDs extending to the observed-frame mid-infrared, we have reliably excluded 22 candidates from our sample which are low-redshift galaxies (or interlopers). Synthesis modelling of the colour evolution of stellar populations predicts that galaxies with z < 4 can also satisfy our UV selection criteria. These galaxies have intrinsically redder near- and mid-infrared SEDs than true high-redshift LBGs. The SED of an example interloper is shown in panel (vii) of Fig. 1 and is easily distinguished from the SEDs of high-redshift LBGs (panels ii–vi). Furthermore, Fig. 1 demonstrates how the addition of the IRAC data has greatly enhanced our ability to screen for such low-redshift galaxies which are generally the brightest sources in the IRAC wavelengths that satisfy our optical selection criteria. These interlopers mostly satisfy the criterion for being extremely red objects (ERO, iAB - KsAB > 2.48, Roche, Dunlop & Almaini 2003) and IRAC-selected EROs (iERO, zAB - μsAB > 3.25 Yan et al. 2004), consistent with being galaxies at z ~ 1–2. The importance of this screening is clear when one considers that most samples of systems satisfying the high-redshift LBG selection criteria distinctly lack confirmatory spectroscopy and several of the recently reported IRAC-detected z > 5 LBGs do not have confirmed spectroscopic redshifts (Egami et al. 2005; Mobasher et al. 2005; Yan et al. 2005). In the case of the z ~ 6 LBG in Mobasher et al. (2005), an interloper solution is more plausible (Dunlop, Cirasuolo & McLure 2007).

Our initial optical selection potentially includes low-mass stars within the Galaxy and QSOs. These are spatially unresolved in the ACS data are therefore straightforwardly excluded. We identified 19 such objects. These objects generally have the brightest visible emission amongst the systems that satisfy our selection criteria (zAB > 23). Vanzella et al. (2006) obtained spectra of four of these objects with sufficient quality for them to be classified as stars, supporting the exclusion of unresolved objects from our robust sample. Had we included them and subjected them to synthesis modelling, their best-fitting models would imply implausibly high SFRs and young ages. Thus, without screening for these objects, our derived ensemble properties would be heavily biased towards young ages and high SFRs.

Finally, as accurate estimates of the ages, masses and SFHs of our galaxies are dependent upon well-sampled SEDs, it is imperative to analyse the objects with the most robust photometry. Therefore, we additionally excluded the results from 47 sources with secure detections in only two or three bands (including i and z), with the remaining constraints being upper limits. There are insufficient data to constrain the models and accurately constrain their physical properties, thus these systems are flagged as having 'insufficient photometry'. A significant fraction of these systems are blended with a nearby source in the IRAC bands. Because blending is purely a random alignment of foreground sources with our high-redshift candidates, there is no reason these should be different to the isolated candidates. Accordingly, we do not find any evidence for a systematic difference in the derived properties of the blended and isolated subsamples. We note that this step may preferentially exclude LBGs with high SFRs, low masses and young ages as these are less likely to be detected in the IRAC bands. Massive, old LBGs...
selected at the same i-band magnitude as younger, lower mass systems are intrinsically brighter in the observed infrared and so require more of the photometric bands to be compromised in order to exclude them in this way.

This culling process renders a final robust sample of 21 galaxies which is the focus of our study. Since each step in the culling process (apart from the last) is unbiased with respect to the physical properties of our high-redshift galaxies, the final robust sample is expected to be representative of the bright, \( z \sim 5 \) galaxy population selected by the Lyman-break technique, with the possibility that the lower mass and younger systems may be underrepresented. The use of the longer wavelength near- and mid-infrared data have enabled us to construct a uniformly selected rest-frame UV sample that is reliable. Fig. 2 shows the magnitude distribution of the robust sample in comparison to all objects satisfying our selection criteria and the culled members. As expected, we find that the star/QSO candidates and low-redshift galaxies are in the most part the brightest sources that satisfy our initial selection criteria. The histograms of the robust sample and the LBG candidates flagged as having insufficient photometry suggest that the former comprises the brighter members of the \( z \sim 5 \) population and the latter the fainter members. Indeed 6 LBGs from the robust sample, and 9 candidates with insufficient photometry, have been spectroscopically confirmed to be \( z \sim 5 \) LBGs (see Section 4.1, Vanzella et al. 2005).

**3 EVOLUTIONARY STELLAR SYNTHESIS MODELLING**

Using a library of synthetic spectra (Bruzual & Charlot 2003), we modelled the SED of each LBG candidate simultaneously deriving photometric redshifts and the key properties of age, extinction, SFR and stellar mass. We explored a range of SFHs (constant SFR, instantaneous burst, and exponentially decaying SFRs with e-folding time-scales ranging from 10 Myr to 1 Gyr). The UV emission from galaxies is dominated by the population of short-lived massive OB and A stars. Models of continuous star formation enable the production of these massive stars even at old ages. In contrast, massive stars die away rapidly in an instantaneous burst model and conspicuous UV emission is only produced at very young ages. For a given initial mass function (IMF), model fits with these two SFHs will bracket the possible age range of the galaxies. Our emphasis on the constant star formation model therefore provides upper limits to the best-fitting stellar ages. For this reason we concentrate our analysis on the results obtained for a constant SFR. The effects of adopting alternative SFHs on our results are discussed in Appendix A.

For all of our models, we used a Salpeter stellar IMF between 0.1 and 100 \( M_{\odot} \). The actual IMF is unconstrained for our objects. A steep rise down to the lower mass cut-off is likely unrealistic in view of the turnover below 1 \( M_{\odot} \) inferred for the local IMF (e.g. Kroupa 2001; Chabrier 2003), and recent comparisons of dynamical masses and photometric stellar masses suggest that Kroupa/Chabrier-type IMFs would be more appropriate at higher redshift as well (e.g. F"orster Schreiber et al. 2006b). The main impact of changing the IMF on our SED modelling is on the derived masses and SFRs which, for a given rest-frame V-band luminosity, would be about a factor of 1.4–2 lower with the Kroupa (2001) or Chabrier (2003) IMFs (see Bruzual & Charlot 2003; see also the discussion by Papovich, Dickinson & Ferguson 2001, in the context of SED modelling of \( z \sim 3 \) LBGs). At \( z \gtrsim 2 \), and more so at \( z \sim 5 \), top-heavy IMFs with a larger proportion of massive (\( > 10 M_{\odot} \)) stars, or even extremely massive (\( > 100 M_{\odot} \)) stars formed from gas of primordial abundance (‘Population III’ stars) may be an issue (e.g. Yoshida, Bromm & Hernquist 2004; Baugh et al. 2005; Schneider et al. 2006). If so, using such an IMF in the modelling would lead to a reduction of the derived stellar masses and SFRs.

We adopted Bruzual & Charlot (2003) models with a metallicity of one-fifth solar and, for consistency, a Small Magellanic Cloud-type (SMC-type) dust extinction law (Prévot et al. 1984; Bouchet et al. 1985). Observational constraints on the metallicity of \( z \sim 5 \) galaxies are scarce; however, the metallicities derived from absorption lines in the spectra of eight \( z \sim 5 \) LBGs in the region of the Hubble Deep Field North are \( Z \sim 0.2 Z_{\odot} \) (Ando et al. 2004) suggest that our choice of 0.2 \( Z_{\odot} \) is reasonably representative. For each individual galaxy, best-fitting parameters were derived from minimization of the reduced \( \chi^2 \) statistic. All model fitting followed standard procedures applied in similar studies of high-redshift galaxies (e.g. Sawicki & Yee 1998; Papovich et al. 2001; Shapley et al. 2001; F"orster Schreiber et al. 2004; Shapley et al. 2005; Papovich et al. 2006; Yan et al. 2006a). We assumed a constant marginalization for each of the models. While our results are marginalized over the extinction law, metallicity, SFR and IMF, we have actually explored a range of all of these parameters (see Appendix A) but the results presented correspond to our preferred single values of these properties as described above. Detailed aspects of the modelling procedure will be described in a forthcoming paper (F"orster Schreiber et al., in preparation).

We note that it is difficult to differentiate between the exact metallicity, extinction by dust and SFHs for each individual galaxy based solely upon the goodness-of-fit because of degeneracies among these model parameters. Therefore, to determine the confidence intervals for the modelled properties, we ran 500 Monte Carlo simulations for each object. We applied the same best-fitting procedure after perturbing the input broadband photometry assuming the photometric uncertainties are Gaussian, as indicated by our background noise fluctuations analysis (see Section 2). The results of these simulations provide the probability distribution in parameter space for each source. By combining these individual probability distributions, we derived those for the properties of the ensemble of sources (see e.g. Papovich et al. 2001 for an analogous approach). Example combined probability distributions for the age, stellar mass, SFR and extinction for all of the galaxies in the robust sample are shown in Fig. 3. These diagrams show the probability that any galaxy satisfying the Lyman-break criteria has of having those properties. From these we can therefore determine the characteristic properties of the
Lyman-break galaxies at $z \sim 5$

4 ENSEMBLE PROPERTIES OF THE ROBUST SAMPLE OF $Z \sim 5$ LBGs

4.1 Redshifts: photometric and spectroscopic

The LBGs in the robust sample have best-fitting photometric redshifts in the range 4.60 to 5.54 ($\langle z \rangle_{\text{median}} = 4.8$) as expected given our initial photometric selection.$^2$ Our photometric redshifts agree exceptionally well (within 2$\sigma$, or better) with spectroscopic redshifts where available for both the high-redshift LBGs and the low-redshift interlopers (see Fig. 4 and Table 1).

As part of the public spectroscopic surveys of the CDF-S conducted by ESO [Vanzella et al. 2005, 2006 (but also see v1.2 release http://www.eso.org/science/goods/spectroscopy/CDFS_Mastercat/)], spectroscopy has been performed for 7 LBGs from our robust sample, 6 of which are confirmed to be at $z \sim 5$. The low signal-to-noise ratio of the spectrum of the remaining robust LBG prevented assignment of a redshift. This high confirmation rate reinforces that our selection of $z \sim 5$ LBGs is robust. Spectroscopic redshifts were also secured for 17 additional sources: 4 are stars, 4 are low-redshift interlopers (all agreeing with our photometric/morphological classification) and 9 are confirmed to lie at $z \sim 5$ and are part of our ‘insufficient photometry’ subsample which we expect includes genuine $z \sim 5$ LBGs. The right-hand panel of Fig. 4 shows the $z$-band magnitude and redshift distributions of the spectroscopically confirmed redshift five LBGs from the robust sample and those flagged as having insufficient photometry. The latter are slightly fainter than the robust sample while the redshift distribution is similar indicating bona fide fainter LBGs are among the sources flagged as having insufficient photometry.

4.2 Stellar Masses, ages, SFRs and extinction

The rest-frame SEDs of the majority of our prime candidates are very blue from the far-UV to the visible, as is expected for young stellar populations with no more than moderate dust obscuration. The results of our stellar evolutionary synthesis modelling with the parameters specified in Section 3 yield the following typical properties for the galaxies. These are typically strongly star-forming galaxies with a median SFR of $40 M_\odot$ yr$^{-1}$. The median photometric stellar mass is $2 \times 10^{9} M_\odot$, about a factor of 10 lower than LBGs at $z \sim 3$ (Papovich et al. 2001; Shapley et al. 2001). The stellar mass estimates are the most robust of all derived properties, varying by a factor of 2–5 depending on the model assumptions (see Appendix A). While a large spread in the best-fitting age is seen amongst individual sources in the sample, the median age is relatively young, $\sim 25$ Myr. The best-fitting models imply only moderate extinction with a median value in the $V$-band of $A_V = 0.3$ mag. Models including extinction at this level fit the SEDs of the $z \sim 5$ LBGs better than models without extinction.

$^2$ Using standard procedures (Madau et al. 1996) we estimate the redshift range our selection criteria are sensitive to. This range is determined following the implementation in Lehner & Bremer (2003). Standard local galaxy templates were modified to account for IGM opacity along the line of sight shortward of Ly$\alpha$ (Madau et al. 1996). They were then further modified using the redshift dependent Gunn–Peterson absorption of Ly$\alpha$ as described in Fan et al. (2006). This results in star-forming galaxies lying between $z \sim 4.6$ and 6 being able to satisfy our selection criteria.
that these young sources have stellar masses mal best-fitting ages younger than this. In addition, Fig. 3(a) shows consistent with the majority (two-thirds) of the galaxies having for-68 per cent of the age distribution lies at ages less than 100 Myr, young ages. As indicated by the contours shown in Fig. 3, more than in age extends over 1 Myr to 1 Gyr, there is a clear concentration at the stellar population. While the ensemble probability distribution the parameters of mass, SFR and extinction as a function of age of 5 LBGs. Fig. 3 shows the combined probability distributions for 3 simulations to characterize the properties of the ensemble of z ∼ 5 LBGs from our robust sample. Two σ error bars on the photometric redshift are overplotted. The figure excludes a low-redshift interloper which has an X-ray counterpart (XCDSS265) and is likely to be AGN-hosting, therefore the results of the stellar evolutionary synthesis modelling does not make sense in this case. As a guide, the line z_{spec} = z_{phot} is overplotted. Right-hand panel: z-band magnitude distribution of the spectroscopically confirmed LBGs. As in Fig. 2 the black/shaded histogram corresponds to galaxies in the ‘robust’ sample.

Table 1. Breakdown of photometric and spectroscopic redshifts for all of the LBG candidates. The z_{phot} column refers to the nominal best-fitting redshift determined from our modelling and the z_{spec} to spectroscopic redshifts from the literature.

<table>
<thead>
<tr>
<th>Category</th>
<th>Total (1a)</th>
<th>z_{phot} ≤ 4 (1b)</th>
<th>z_{phot} &gt; 4 (1c)</th>
<th>Attempted (2a)</th>
<th>z_{spec} ≤ 4 (2b)</th>
<th>z_{spec} &gt; 4 (2c)</th>
<th>Unassigned (2d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UV selection</td>
<td>109</td>
<td>23</td>
<td>86</td>
<td>34</td>
<td>8</td>
<td>15</td>
<td>11</td>
</tr>
<tr>
<td>Robust sample</td>
<td>21</td>
<td>0</td>
<td>21</td>
<td>7</td>
<td>0</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>Insufficient photometry</td>
<td>47</td>
<td>1</td>
<td>46</td>
<td>14</td>
<td>0</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>Star/QSO</td>
<td>19</td>
<td>0</td>
<td>19(^{a})</td>
<td>5</td>
<td>4</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Interlopers</td>
<td>22</td>
<td>2</td>
<td>0</td>
<td>8</td>
<td>4</td>
<td>0</td>
<td>4</td>
</tr>
</tbody>
</table>

Columns (1a)–(1c) refer to the results of the SED modelling for all candidates (109) that satisfy our original UV-selection, and columns (2a)–(2d) for those of the 109 candidates which have been spectroscopically followed-up. (1a) Total number of sources satisfying our initial selection criterion. (1b and 1c) The numbers of LBG candidates with photometric redshifts above and below z = 4. (2a) Total number of LBG candidates from our initial sample that have had spectroscopic measurements. (2b) Number of candidates for which the spectra were of insufficient quality to definitively assign a redshift. (2c and 2d) The numbers of sources with confirmed spectroscopic redshifts above and below z = 4.

\(^{a}\)Best-fitting redshifts of z_{phot} > 4 are produced for all objects classed as stars/QSOs due to the the strong break in their SEDs being identified with the Lyman break and because their SEDs are fit with inappropriate star-forming galaxy templates.

As discussed in Section 3, we use the results of our Monte Carlo simulations to characterize the properties of the ensemble of z ∼ 5 LBGs, Fig. 3 shows the combined probability distributions for the parameters of mass, SFR and extinction as a function of age of the stellar population. While the ensemble probability distribution in age extends over 1 Myr to 1 Gyr, there is a clear concentration at young ages. As indicated by the contours shown in Fig. 3, more than 68 per cent of the age distribution lies at ages less than 100 Myr, consistent with the majority (two-thirds) of the galaxies having formal best-fitting ages younger than this. In addition, Fig. 3(a) shows that these young sources have stellar masses <10^{10} M_{⊙}, typically ~10^{9} M_{⊙}, and Fig. 3(b) suggests they are the most strongly star-forming systems within our sample. This is unsurprising as they must have the lowest UV mass-to-light ratios in our sample given their low mass.

The remaining third of our sample have best-fitting masses of order 10^{10} M_{⊙} and ages older than a few hundred million years. These older galaxies are analogous to several galaxies recently reported (Chary et al. 2005; Dow-Hygelund et al. 2005; Egami et al. 2005; Eyles et al. 2005; Mobasher et al. 2005; Schaerer & Pelló 2005; Yan et al. 2005, 2006a) that lie at similar or slightly higher redshifts (z ∼ 6–7) than ours, where the presence of a discontinuity between the near and mid-infrared bands in the SED is identified with the rest-frame Balmer/4000 Å break (Fig. 1). This break is indicative of more evolved stellar populations, where the emission from stars with ages of several hundred million years dominates over that from the short-lived massive stars that produce the UV emission. The absence or weakness of a discontinuity between the K_{s}-band and 3.6-μm photometry points in the SEDs of the majority of our sample of galaxies with younger best-fitting ages strongly limits the possible contribution to the integrated stellar light by such similarly evolved stellar populations. Indeed, the lack of this discontinuity constrains their best-fitting ages to less than ~100 Myr. While old and massive systems are present in the sample, our results clearly indicate that a substantial fraction (two-thirds) of galaxies at z ∼ 5 satisfying the Lyman-break selection criteria are dominated by a young, intensely star-forming component. Similarly young ages and moderate masses (ages ≤ 45 Myr and stellar masses ~10^{9} M_{⊙}) are
found for IRAC undetected i-band dropouts (z ~ 6) LBG candidates recently reported by Yan et al. (2006a).

In this section we have reported on the typical physical properties of the sample of luminous z ~ 5 LBGs for our adopted modelling assumptions. We have extensively investigated the effects of varying the input model parameters on the derived properties and find the key properties of young ages and moderate masses are robust under a wide range of model assumptions. We discuss the effects of varying the input parameters in Appendix A (see also N. M. Förster Schreiber et al., in preparation).

5 COMPARISON TO LBGS AT REDSHIFT 3

5.1 Stellar masses, ages, SFRs and extinction

In this section we compare the properties of our z ~ 5 sample with those published for the z ~ 3 LBG sample from Shapley et al. (2001) which is matched in rest-frame UV luminosity. The SEDs for both samples span the same rest-frame wavelength range and modelling shows significant differences in the stellar masses and ages derived even for identical modelling assumptions. Because of this and the matched selection, we can only ascribe these differences to intrinsic differences in the properties of LBGs at these two epochs.

The i-band selection limit of i_{AB} < 26.3 chosen for our z ~ 5 sample is matched to the typical magnitude limit of spectroscopically confirmed samples of LBGs at z ~ 3. This limit (R_{AB} < 25.5), is sensitive to z ~ 3 LBGs that are ~1 mag fainter than m^{*}_{1700Å,AB} = 24.48 (Steidel et al. 1999), the R-band maps to 1700 Å in the rest-frame at z ~ 3. This enables us to compare the ensemble properties of our robust sample of z ~ 5 LBGs to those obtained for 74 z ~ 3 LBGs with apparent magnitudes greater than 0.1 m^{*} from the sample analysed by Shapley et al. (2001). As well as matching our samples by magnitude, in order to make a fair comparison we have modelled the SEDs of our robust sample of z ~ 5 SEDs using the same assumptions as Shapley et al. Specifically, we used solar metallicity model spectra generated with the Bruzual & Charlot (2003) population synthesis code, a constant SFH, a Salpeter IMF^3 and a Calzetti attenuation law (Calzetti et al. 2000). Note that this is a different extinction law and metallicity than those used in previous sections, but allows a direct comparison between the two samples. Any differences in the results indicate intrinsic differences in the properties of the two samples, either in properties like mass and SFR, or that different extinction laws or metallicities are required at the two epochs.

Fig. 5 shows the results of this comparison for the best-fitting stellar masses, ages, extinctions and SFRs obtained for a constant SFH from the z ~ 3 LBG sample of Shapley et al. (2001) (shaded histograms) and the results for our robust z ~ 5 sample (line-filled histograms). While the derived extinctions are well matched, this comparison clearly shows significant differences in the ages, masses and SFRs between the samples at z ~ 3 and 5. The z ~ 5 sample shows young typical ages (≤10 Myr), in contrast the z ~ 3 LBGs are significantly older (~320 Myr). The typical stellar mass (few × 10^{9} M_{⊙}) of z ~ 5 LBGs is ~5–10 times lower than the z ~ 3 sample. Extremely high SFRs are estimated (~500 M_{⊙} yr^{-1}) for the z ~ 5 LBGs, a factor of 10 higher than the z ~ 3 sample. Since we have compared the properties of similarly selected galaxies, based on the same rest-frame UV measurements, to the same UV luminosity, which have

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[^3]: They assume a slightly higher upper mass cut-off of 125 M_{⊙} than our assumed 100 M_{⊙}, however this slight increase has an insignificant effect on the generated models and resultant properties.
been modelled under the same assumptions, these differences can unequivocally be ascribed to inherent differences in the properties of the two samples of LBGs.

Moreover, this comparison demonstrates that adopting Calzetti extinction law and solar metallicity may not be appropriate for this sample of bright $z \sim 5$ LBGs. Implausibly young ages ($<10\,\text{Myr}$) and excessively high SFRs ($>10^3\,\text{M}_\odot\,\text{yr}^{-1}$) are seen for a large fraction of the $z \sim 5$ population. The fact that the ages are so significantly younger than the $z \sim 3$ LBG population (see top left-hand panel Fig. 5) is an indication that the SEDs of $z \sim 5$ LBGs are even ‘bluer’ than their $z \sim 3$ counterparts. The combination of the adopted extinction law and the high-metallicity templates results in these extremely young ages and high SFRs (see the discussion in Appendix A and also Papovich et al. 2001).

As discussed in Section 3, evidence suggests our consistent choice of $0.2\,Z_\odot$ and the SMC extinction law is suitable to model the blue SEDs of our $z \sim 5$ LBGs. Shapley et al. (2001) have discussed the suitability of the Calzetti plus solar metallicity models for $z \sim 3$ LBGs. In Fig. 6 we show the comparison between the properties of LBGs at $z \sim 3$ and 5 under these appropriate (but different) assumptions. We have elected to show the probability distribution of properties obtained from our Monte Carlo simulations of the $z \sim 5$ LBGs to give less importance to the formal best-fitting solutions which can be sensitive to the modelling assumptions. Since the probability histograms follow the same distribution as the best-fitting parameters themselves (see the examples of stellar mass and SFR in Fig. 7), our comparison using the probability distributions is reasonable.

Fig. 6 shows that the distributions of SFRs are extremely well matched, however, there are clear differences in the distributions of stellar mass, age and extinction. The typical stellar mass of LBGs is a factor of 10 lower at redshift 5 than at redshift 3. Similarly, the distribution of ages shows more sources have ages $<100\,\text{Myr}$ in the $z \sim 5$ sample than the $z \sim 3$ sample. There is an apparent

![Figure 6](https://academic.oup.com/mnras/article-abstract/377/3/1024/1078127)

**Figure 6.** The shading and lines are as in Fig. 5 but now showing the distributions of properties derived from our Monte Carlo simulations of the properties of $z \sim 5$ LBGs from our robust sample (line filled histograms) obtained with $0.2\,Z_\odot$ templates and a SMC extinction law (see text for details).

![Figure 7](https://academic.oup.com/mnras/article-abstract/377/3/1024/1078127)

**Figure 7.** This figure shows that the distribution of properties derived from our Monte Carlo simulations (line filled histograms) trace the distributions of nominal best-fitting (shaded histogram) properties well. Stellar masses and SFRs are shown, ages and extinctions show similar agreement. The solid vertical line indicates the median value.
difference in the distribution of extinctions but this can largely be attributed to differences in the modelling assumptions (Appendix A). This is corroborated by the fact that the extinction distributions overlap almost entirely when the same modelling assumptions have been made as we have shown in Fig. 5. Furthermore, a comparison to the results for similarly luminous $z \sim 3$ LBGs studied in Papovich et al. (2001), assuming a Calzetti extinction law but with the $0.2 Z_\odot$ templates, shows similar extinction for the $z \sim 3$ LBGs as is seen in Fig. 6. Thus the difference in the extinction between $z \sim 5$ and $z \sim 3$ LBGs seen in Fig. 6 is mostly a consequence of the adopted extinction law and not the metallicity of the templates.

Papovich et al. (2001) have comprehensively discussed the effects of different model assumptions on the derived properties of a faint sample of $z \sim 3$ LBGs. Their combined probability distributions highlight the problems associated with using the Calzetti extinction law with the low metallicity Bruzual & Charlot (2003) templates. In their fig. 9(b), they show the probability distribution resulting from the SED modelling assuming a Calzetti extinction law with the bluer $0.2 Z_\odot$ metallicity templates. A clear extension of sources with extremely young ages ($\lesssim 10$ Myr) and high $A_V$ ($\gtrsim 2$) is seen. This extension almost disappears under a Calzetti law with $Z_\odot$, and with the SMC law for either the $0.2$ or $1 Z_\odot$ models (cf. their figs 9b with 9d, 12b and 12d for a Salpeter IMF).

Thus, adopting the Calzetti law with the solar or low metallicity templates would only act to reduce the derived ages of the $z \sim 5$ LBGs and results in stellar masses that are $5-10$ times lower than $z \sim 3$ LBGs, that is, leaving our previous conclusions of young ages and moderate masses for $z \sim 5$ LBGs unaffected. Moreover, under all suitable assumptions for the extinction law and consistent metallicities (i.e. $1 Z_\odot$ with the Calzetti law, $0.2$ or $1 Z_\odot$ with SMC), we find that galaxies with ages ($< 100$ Myr) and masses ($\sim 10^9 M_\odot$) dominate samples of bright LBGs at $z \sim 5$. Our analysis of the probability histograms and distributions shown in Figs 3 and 6 shows this fraction to be $\gtrsim 70$ per cent. However, while $z \sim 3$ LBGs with such young ages and similar stellar masses are not unknown (e.g. Papovich et al. 2001; Shapley et al. 2001), they are less than half as prevalent in LBG samples at $z \sim 3$ than at $z \sim 5$ ($\lesssim 30$ per cent). This unequivocal change in the age and mass of the dominant population in luminous LBG samples separated by $\sim 1$ Gyr, implies that at $z \sim 5$ is an epoch where the majority of LBGs are recently formed and are in the process of accumulating their first significant mass.

5.2 Duty cycle and bias

We have shown in the previous sections that the dominant population of LBGs in our $z \sim 5$ sample is younger and of lower mass than that in $z \sim 3$ LBG samples with similar UV luminosities. Since the majority of LBGs at $z \sim 5$ are so young, it is inevitable their detectability is highly stochastic and this stochasticity impacts upon the interpretation of other statistical properties such as their clustering strength, number density and bias.

Papovich et al. model $z \sim 3$ LBGs with the same metallicity (Bruzual & Charlot 2003) templates and IMF as we have assumed. However, they give best-fitting results for individual galaxies only with the Calzetti extinction law. Since Papovich et al. give best-fitting results for a range of SFHs we consider only those fit with constant star formation and those with best-fitting ages less than the e-folding time-scales of their ‘best-fitting’ exponentially decaying SFH model. The latter condition for age $< \tau$ gives similar results to constant star formation. In addition, we considered only those LBGs from this faint sample which are matched in luminosity to the $z \sim 5$ samples, $V \sim 24.8$. 10 LBGs from Papovich et al. satisfied these criteria.

Lehnert & Bremer (2003) showed that the comoving number density of $z \sim 5$ LBGs selected in a similar manner to our robust sample was a factor of 3 lower than that of similar luminosity LBGs at $z \sim 3$ and 4 (Steidel et al. 1999). If the LBGs at both epochs had identical properties then this can be directly related to evolution in the comoving number densities of the haloes that they occupy. Clearly, this naive picture is complicated by the clear difference in properties of the two samples in the previous section. Moreover, the younger ages of the higher redshift sample imply a shorter duty cycle for the LBG, related to the length of time a galaxy would be detected as a UV luminous LBG.

Given that the average lifetime of the $z \sim 5$ LBGs of $\sim 25$ Myr and that the look-back time spanned by our survey (325 Myr over the redshift range of the $z \sim 5$ LBGs $4.4 < z < 5.6$), suggests that luminous members of the $z \sim 5$ LBG populations have a duty cycle of 0.08. A similar estimate for $z \sim 3$ LBGs by Shapley et al. (2001), renders a duty cycle of 0.5, significantly longer than at $z \sim 5$. So across the two sample volumes, the higher redshift sample represents systems $\sim$thirteen times as numerous as those detected, whereas the lower redshift sample misses only half of the potential LBGs in the volume. Clearly, the young ages of the bulk of the high-redshift sample have a significant effect on the bias of these sources.

LBGs have been long known to be a significantly clustered population (e.g. Adelberger et al. 1998; Giavalisco et al. 1998; Ouchi et al. 2004b; Lee et al. 2006).5 Clustering analysis of 23.5 $< R_{\text{eff}} < 25.5$ LBGs at $z \sim 3$ suggests that LBGs reside in dark matter haloes of masses $10^{11.2-11.8} M_\odot$ (Adelberger et al. 2005) consistent with recent estimates of the dynamical virial mass of the DM haloes of LBGs determined from the rotation curves of $z \sim 3$ LBGs (Weatherley & Warren 2005; Nesvadba et al. 2006). For $z \sim 5$ LBGs, Lee et al. (2006) suggest slightly lower halo masses may be plausible ($M_{\text{halo}} \sim 10^{11} M_\odot$) however the uncertainties are too large to see a significant difference between the $z \sim 3$ and $z \sim 5$ populations. This conclusion is similar to that of Ouchi et al. (2004b) who found an increase (of marginal significance) in the correlation length with increasing redshift which is consistent with a constant halo mass of $10^{12} M_\odot$ over $z = 3-5$. Again, however, the uncertainties, especially for the highest redshift LBGs, were large. Given this, and in the absence of dynamical measurements of $z \sim 5$ LBGs, we adopt the $z \sim 3$ mass range ($10^{11.2-11.8} M_\odot$, Adelberger et al. 2005) for the dark matter haloes of $z \sim 5$ LBGs. Given that the comoving number density of underlying dark matter haloes of sufficient mass to host such LBGs is evolving strongly from $z = 5$ to 3 (Mo & White 2002), the bias of the LBGs must be increasing with redshift (Ouchi et al. 2004b).

The uncertainties in the clustering statistics of LBGs at $z \sim 5$ are still relatively large. The determination of accurate halo masses at $z \sim 5$ will come from a analysis of the clustering statistics of a sufficiently large sample of either spectroscopically confirmed or photometrically robust LBGs (e.g. Ouchi et al. 2004b). As we have shown in this paper, the latter requires a sample defined using both visible and infrared bands to exclude low-redshift galaxies. Until this is done comprehensively, clustering statistics from samples selected by optical photometry alone or those that only include shallow infrared data, should be interpreted with caution.

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5 Further analysis on the clustering strength of $z \sim 5$ LBGs will be presented in a forthcoming paper (A. Verma et al., in preparation).
5.3 Evolution of the global SFR and stellar mass densities

5.3.1 Global star formation rate density

The evolution in the SFR density (SFRD) with redshift has been a crucial tool in our understanding of the evolution of galaxies in an ageing Universe. The ground-breaking ‘Madau-plot’ (Madau et al. 1996) and versions thereafter have clearly defined the era of peak star formation activity in the Universe (z ≈ 1–2; e.g. Connolly et al. 1997; Heavens et al. 2004), however constraining the SFRD at higher redshifts is still an issue of debate with direct observed estimates suggesting a decline for z ∼ 3, while estimates based on integrating over the luminosity function and theoretical predictions (Somerville et al. 2004; Nagamine et al. 2006) imply a constant value or shallow decline beyond the peak at z ∼ 2 (e.g. Steidel et al. 1999; Bunker et al. 2004; Giavalisco et al. 2004a; Ouchi et al. 2004a; Bouwens et al. 2006; Bouwens & Illingworth 2006; see also Hopkins & Beacom 2006 for a compilation and references therein).

The model of Hernquist & Springel (2003) and the TVD hydrodynamical simulations of Nagamine et al. (2006) suggest the SFRD might still be increasing at z ∼ 5.

Our results from the SED modelling of z ∼ 5 LBGs has an impact on this. The SFRD derived from the best-fitting SFRs for LBGs in our sample is compared in Fig. 8 to several recent observational determinations and model predictions from the literature. This is determined from the total SFR for our robust sample, corrected for the number of true z ∼ 5 LBGs we expect in our total sample of 109 sources (all except the 40 per cent interloper fraction), incompleteness at our magnitude limit (10 per cent\(^6\)) and accounting for galaxies to 0.1L\(^*\),\(^7\) over our survey volume. Namely, the survey volume is given by the area of the field, multiplied by the depth in redshift space between the minimum and maximum redshifts that can satisfy our initial selection criteria. However, not all sources would remain in our magnitude limited sample because of cosmological dimming and increased intervening hydrogen opacity with redshift (Lehnert & Bremer 2003). Making the assumption that all sources are at the maximum possible redshift to remain in the sample (i.e. they are close to the magnitude limit of i\(_{AB}\) = 26.3) gives a volume probed of ∼40 per cent of the maximum notional volume (consistent with fractions determined from detailed calculations Lehnert & Bremer 2003, and E. Stanway, private communication). The SFRD accounting for this effective survey volume is shown in Fig. 8. For consistency with the models, the SFRs determined have been corrected to a Chabrier/Kroupa IMF, rather than the Salpeter IMF we have used in the modelling, by dividing by a factor of 1.6 (Nagamine et al. 2006).

The high SFRD determined supports no more than shallow decline in the SFRD at high redshift, consistent with the theoretical predictions of Nagamine et al. (2006) and Hernquist & Springel 2003, however lies above the semi-analytic accelerated quiescent model of Somerville, Primack & Faber (2001).

SFRs can also be derived by scaling the intrinsic rest-frame UV luminosities of sources. The additional data points shown in Fig. 8 are derived as such. For starbursts younger than ∼100 Myr, the ratio of SFR to UV luminosity declines with age, levelling off at ∼100 Myr. This is due to the time it takes to build up a UV luminous stellar population in such a galaxy, the levelling-off occurring once their birth and death rates match. In part owing to this effect, a z ∼ 5 sample matched in intrinsic UV luminosity with a z ∼ 3 sample will have higher SFRs for the typically younger ages we infer. Here we note that the UV luminosity density declines by a factor of ∼3 between z = 4 and 5 (Lehnert & Bremer 2003). Because of the younger ages at higher redshifts, this must be an upper limit to the decline in SFRD, at least for the more luminous LBGs. A detailed exploration of this issue is left to a forthcoming paper ( Förster Schreiber et al., in preparation).

5.3.2 Global stellar mass density

The evolution in the global stellar mass density with redshift places strong constraints on models of the stellar mass assembly in the Universe (Dickinson et al. 2003b). Approximately 50 per cent of the stellar mass in galaxies had formed by z ∼ 1–1.5, with ∼10 per cent in place by z ∼ 3 (Dickinson et al. 2003b; Rudnick et al. 2003, 2006). Accurately constraining the evolution of this property with redshift requires mass-selected (or mass-limited) samples at different epochs. While our sample of luminous LBGs is not mass selected, we can nevertheless place limits on the formation of stellar mass soon after the end of reionization. We have determined the stellar mass in our survey volume after applying the incompleteness corrections described in the preceding section (with the exception of the correction to 0.1L\(^*\)). The stellar mass density at z ∼ 5 is ρ\(_{\ast}\) ∼ 1.5 × 10\(^{-5}\) M\(_{\odot}\) Mpc\(^{-3}\) (Ω\(_{\ast}\) ∼ 1.1 × 10\(^{-5}\)), for a Salpeter IMF. For consistency with the published modelling, Nagamine et al. (2006) for example, we reduce this value by 1.4 to account for the difference between the Salpeter IMF and the Chabrier/Kroupa IMF used in the models, as shown in Fig. 9. This limit represents ∼0.3 per cent of the total stellar mass of galaxies seen today and

\(^{6}\)Gwyn, determined from the v1.0 release of the ACS data see http://www.astro.uvic.ca/grads/gwyn/virmos/cdfs/index5.html.

\(^{7}\)Assuming the z ∼ 3 luminosity function of Steidel et al. (1999) (α = −1.6) since the faint end slope of the z ∼ 5 luminosity function remains uncertain.
Comparably massive galaxies \((\sim \log_{10} M_\odot)\) lies in the population of massive distant red galaxies (Rudnick et al. 2006). Moreover, at the mass density but at a lower level (a factor of a few) compared to Extending the mass function to lower masses would again increase to be expected given our sample is not selected to be mass complete. It is consistent with recent estimations at high redshift (Stark et al. 2006; Yan et al. 2006a; Eyles et al. 2007). The stellar mass density derived is a lower limit partly because of the stochasticity discussed in Section 5.2. The relatively short duty cycle of these sources suggests that up to \(\sim 12\)-in-13 LGs at \(z \sim 5\) may be missed in our survey. Accounting for this incompleteness places an upper limit on stellar mass density at this epoch for our sources (see Fig. 9). Even after accounting for this, our derived upper limit falls below the predictions of the evolution of mass density with redshift obtained from the integration of the models that plausibly explain the SFRD\((z)\) to high redshift (see Fig. 9). This is to be expected given our sample is not selected to be mass complete. Extending the mass function to lower masses would again increase the mass density but at a lower level (a factor of a few) compared to the duty cycle correction. Moreover, at \(z \sim 2\) as much of the stellar mass density contained within UV-selected samples (Shapley et al. 2005) lies in the population of massive distant red galaxies (Rudnick et al. 2006), which are largely missed by UV selection techniques. Comparably massive galaxies \((\gtrsim 10^9 M_\odot)\) in the UV selected sample of Shapley et al. (2005) are an order of magnitude less numerous than the DRGs. Whether such massive galaxies dominate the mass density at \(z \sim 5\) remains to be established.

The apparent discrepancy between these theoretical predictions and the observed estimates for \(z > 1\) has been attributed to incompleteness of the observational data (e.g. Nagamine et al. 2006), or deficiencies in the models, predicting too much stellar mass at high redshift, despite reproducing the SFRD\((z)\). Rudnick et al. (2006) comprehensively discuss both observational estimates and model predictions highlighting the potential causes for the discrepancies from both perspectives (see also the discussion in Gwyn & Hartwick 2005). Notwithstanding, based on the observational data alone, our upper limit implies that \(\sim 1.5\) per cent of the present-day stellar mass density could have already been assembled in luminous LGs in the first 1.2\text{ Gyr}, rising by an order of magnitude \(\sim 1\) Gyr later (Rudnick et al. 2006). This suggests that once the first galaxies had formed, star formation and stellar mass assembly proceeded at a prodigious rate in the early Universe.

5.4 Mass and luminosity densities

We measured the sizes of LGs in the robust sample using the ACS \(r\)-band images. Using the spectroscopic and photometric redshifts, the mean (proper) size of the \(z \sim 5\) LGs is found to be \(1\) kpc. This is a 40 per cent decrease from the mean size of LGs at redshift 3 \((r_e \sim 1.7\) kpc\), which is fully consistent with the known size evolution of UV-selected galaxies (Bouwens et al. 2004; Bremer et al. 2004; Ferguson et al. 2004).

Trujillo et al. (2004) found that there was no or only weak evolution of the stellar mass densities \((\rho_* \sim \rho_0)\) of galaxies with masses \(> 10^{10} M_\odot\) over the redshift range of \(\sim 0.3\). While the results of Trujillo et al. (2004) are incomplete for lower mass galaxies, we find that the stellar mass densities for our LGs at \(z = 5\) are comparable to that found by Trujillo et al. (2004). However, their UV luminosity densities \((\rho_* \sim \rho_0)\) are significantly higher than LGs at \(z \sim 3\) with \(z \sim 5\) LGs producing as much luminosity as \(z \sim 3\) LGs in one-fifth of the volume. This difference cannot be attributed to a low surface brightness, extended component since the ACS images are significantly deeper than our magnitude limit for selection (see Bouwens et al. 2004).

The fact that the stellar mass densities are comparable to star-forming galaxies at low redshifts, while the observed luminosity densities are significantly higher, is indicative that the mass-to-light ratio of such galaxies is evolving with redshift (Trujillo et al. 2004), LGs (and DRGs) at \(z \sim 2\) have \((M/L)\) ratio of \(\sim 0.5\)–1 (Trujillo et al. 2004; Shapley et al. 2005) while we find by \(z \sim 5\) LGs have \((M/L)\) ratio of 0.1. In the hierarchical framework, stellar mass assembly is likely to have occurred in episodic bursts. Low mass-to-light ratios, such as those we are finding for the \(z \sim 5\) LGs, are expected for galaxies at high redshift which are forming stars in a recent burst. These findings are consistent with our contention that these are young (and likely without a significant intermediate age population, see Appendix B), unextinguished intensely star-forming galaxies.

5.5 Lyα emitting galaxies

The spectra of 9 of 15 LGs with spectroscopic redshifts show an emission feature with an asymmetric line profile and continuum break consistent with the being Lyα. For \(z \sim 5\)–6 LGs, Ando et al. (2006) find that luminous LGs are Lyα deficient, with the separation between those which are Lyα emitters occurring at \(\gtrsim M_{\text{AB,1400 Å}} \sim 21.5\) to \(21.0\) mag. They postulate that more luminous LGs are more chemically evolved systems where dust absorbs the Lyα emission, although alternative explanations cannot be ruled out. This is consistent with the ideas put forward by Mori & Umemura (2006) who suggest that Lyα emitting and LGs are evolutionary stages in the chemical enrichment of galaxies that trace the evolution of primeval irregulars to present-day ellipticals. From N-body hydrodynamical simulations with stellar population synthesis they state that the Lyα is produced by cooling shocks in the early, subsolar metallicity evolutionary phase for ages \(\lesssim 300\) Myr. Then, up to 1 Gyr, the stellar continuum increases and the metallicity becomes solar.

We would therefore expect to see a trend in our derived ages and the equivalent width (EW) of Lyα in our sample with older galaxies having lower EWs. Using the ESO-FORS2 spectroscopy, we have crudely estimated the Lyα EWs (ignoring underestimation caused by the blueshifted absorption due to intervening opacity along the line of sight) of the Lyα emission to be \(\sim 20\) Å for all LGs in the robust sample, irrespective of absolute magnitude.
This analysis is particularly appropriate here since we do not find any strong difference in the distributions of mass or SFR suggesting these properties do not influence the presence or absence of Lyα. Furthermore, we find no evidence that the ‘break-only’ galaxies have a higher average extinction than the galaxies exhibiting Lyα in their spectra and therefore attenuation by dust may not be the sole reason why there is a lack of Lyα emission in the break-only LBGs. Rather local conditions must influence the presence and strength of Lyα emission. It may well be that young galaxies have a high covering fraction of neutral gas which becomes successively more ionized as the galaxy ages. The effect of winds and the geometry of the gas may also play a crucial role in the range of ages seen in galaxies without significant Lyα emission.

6 DISCUSSION

We present detailed analysis of the properties of LBGs at $z \sim 5$ with robust and reliable photometry spanning the rest-frame UV to visible. Through a probability analysis we are able to constrain the properties of the ensemble and find that ‘young’ ($<100$ Myr) and moderately massive ($\sim 2 \times 10^9 M_\odot$) galaxies are in fact more than twice as prevalent at $z \sim 5$ (70 per cent) than at $z \sim 3$ (30 per cent). This increased fraction of young and moderately massive galaxies suggests that at redshift 5 we are seeing an era of widespread stellar mass assembly in the early evolution of galaxies. Based on these properties, we discuss three key characteristics of this population that emerge from our analysis.

6.1 Progenitors of present-day early-type galaxies or bulges

The luminous $z \sim 5$ LBGs studied here are undergoing a period of intense, recent star formation that dominates their rest-frame UV-to-visible emission. Their compact sizes, as measured from the HST images, show that the UV emitting regions are small (mean and median half-light radius of $\sim 1$ kpc). In their short lifetimes, each of these galaxies has already assembled $\sim 2 \times 10^9 M_\odot$ of stars within this radius. The inferred stellar mass surface density ($\mu_\ast \sim 6 \times 10^4 M_\odot$ kpc$^{-2}$) is comparable to the bulge and spheroidal components seen in present-day typical ($L^*$) galaxies (e.g. $\langle \mu_\ast \rangle \sim 5 \times 10^4 M_\odot$ kpc$^{-2}$, Galaz et al. 2002).

From a study of nearly 400 000 low-redshift galaxies drawn from the Sloan Digital Sky Survey, Kauffmann et al. (2006) have shown that significant differences between the structural parameters of early and late-type galaxies are highly dependent on their mass surface densities, rather than the total mass of the galaxies. Specifically, they find that the concentration parameter ($C > 2.5$) and stellar mass surface densities ($\mu_\ast > 3 \times 10^8 M_\odot$ kpc$^{-2}$) correspond to the regime of galaxy spheroids and bulges, independent of the total stellar mass of these systems. Above this threshold of mass surface density, they find that star formation is increasingly suppressed in local galaxies (the specific star formation is low) and must have ceased many Gyr ago. As a consequence, Kauffmann et al. (2006) hypothesize that with increasing compactness and surface density of the galaxy, stars were formed in short, vigorous episodes at high redshift, with extended periods of inactivity (Kauffmann et al. 2006 characterized this as the gas consumption time-scale, $t_{\text{consum}} \propto \mu_\ast^{-1}$). This analysis is particularly appropriate here since we do not find high stellar masses which is often taken as evidence for being progenitors of early-type galaxies; we instead find very high-mass surface densities. Given the circumstantial evidence that the $z \sim 5$ LBGs in our sample drive winds (see Section 6.2.1), have young ages and short duty cycles, it is also plausible that these galaxies will grow in strong bursts of star formation. So while we cannot know the evolutionary path of this population of galaxies, their overall mass surface densities suggest that they are the progenitors of early-type galaxies or bulges, and favours the ‘inside-out’ galaxy formation scenario.

The star formation that dominates the UV-to-visible SEDs of the $z \sim 5$ LBGs in our sample is likely to be such a burst of star formation in which a significant fraction of the stellar mass of the system has been formed. A simple estimate of the relating the dynamical time-scale to the mass and size of a galaxy is

$$t_{\text{dynamical}} = r \frac{r}{V} \approx \eta^{1/2} \frac{M^{3/2}}{G^{1/2}},$$

where $V$ is the characteristic (virial) velocity of the system, $\eta$ is a geometrical correction factor that depends on the mass distribution within the system, $r$ is the radius or physical scale of the system, $M$ is the mass of the system, and $G$ is the gravitational constant. Depending upon the mass distribution for a given galaxy, $\eta$ is $\approx 5$. (Binney & Tremaine 1987; Rix et al. 1997). With a median measured half-light radius of $\sim 1$ kpc and a mass of $2 \times 10^9 M_\odot$, we estimate that the dynamical time-scale of the galaxies in our sample is of the order of 20 Myr. Therefore, the intense star formation in the majority of the $z \sim 5$ LBGs (age $\sim 100$ Myr) has been typically proceeding for approximately one to five dynamical time-scales. Starbursts, the youngest, large-scale star-forming events seen in nearby galaxies have comparable durations (Lehnert & Heckman 1996; Kennicutt 1998; Förster Schreiber et al. 2003). A system that has assembled a significant fraction of its stellar mass over the last few dynamical time-scales is in essence a galaxy in the process of formation. Thus, the young galaxies in our sample are likely to be members of the long sought-after population of primeval galaxies in the process of significant stellar mass build-up.

Further support of the progenitor scenario arises from analysis of the clustering of the $z \sim 5$ LBGs. The clustering length of $z \sim 5$ LBGs implies that $L > L^*$ at $z \sim 5$ stay reside in dark matter haloes with masses of the order of $10^{11-12} h_5^3 M_\odot$ (Ouchi et al. 2004b; Lee et al. 2006). While this is comparable to the dark matter mass halo of the Milky Way and to the haloes of $z \sim 3$ LBGs (Adelberger et al. 2005), this should not be interpreted as supporting that LBGs are the precursors of galaxies like the Milky Way or $z \sim 3$ populations. Linking a population of galaxies at one redshift with another population at another at is fraught uncertainty (see e.g. Moustakas & Somerville 2002). If these galaxies are the progenitors of galaxies like the Milky Way, this would require an evolutionary path whereby the clustering amplitude and halo mass does not grow, the bias decreases, but the baryonic mass would have to increase by over an order of magnitude. In a galaxy conserving model for the growth of structure (Fry 1996), and if we think of the estimated bias of the LBG population as $z \sim 5$ as its bias at birth, would suggest that the bias would decrease with decreasing redshift while the correlation scale would increase (Fry 1996; Moustakas & Somerville 2002). In such a model, the evolution of both the bias and correlation scale suggests that the $z \sim 5$ LBGs could be the progenitors of the red galaxies at $z \sim 1$ and massive early-type galaxies at $z \approx 0$ (Coil et al. 2004; Zehavi et al. 2005). The conclusions would be similar in hierarchical merging models (Moustakas & Somerville 2002; Ouchi et al. 2004b). In either model, it is difficult to say that the $z \sim 3$
and 5 are directly related (except for the large uncertainties in the clustering and bias estimates for the $z \sim 5$ LBGs).

In the hierarchical merging scenario, phase-space density arguments suggest that massive, present-day elliptical galaxies have formed from the merging of high-redshift disc galaxies, which are smaller and denser than disc galaxies seen today (Mao & Mo 1998). If the $z \sim 5$ LBGs represent the early stages of the formation of present-day bulges and spheroids they should have core phase-space densities that are consistent with their present-day descendants. A significantly lower phase-space density would rule out a progenitor scenario. Following Carlberg (1986) and Mao & Mo (1998) the core phase-space density of the typical $z \sim 5$ LBG in our sample is $\sim 10^{-9} M_\odot (\text{pc km s}^{-1})^{-3}$. This is consistent with the core phase-space densities of massive, bright present-day ellipticals and the central region of the Milky Way (Carlberg 1986; Mao & Mo 1998; Wyse 1998; Avila-Reese et al. 2005). While we cannot constrain the evolutionary path of these LBGs, this similarity between the core phase-space densities of our $z \sim 5$ LBGs and present-day bulges and ellipticals, strongly suggests that the central population in these systems is already in place at high redshift.

The young $z \sim 5$ LBGs may therefore represent the formation of the central regions of present-day massive galaxies at the earliest stages of their evolution. If so, their abundance at a look-back time of 12–13 Gyr is consistent with the age of the dominant stellar population in the Galactic Bulge (Rich 2005) and its proposed formation in short bursts 1–2 Gyr after the big bang (Zoccali et al. 2006).

6.2 Enrichment of the intragalactic and intergalactic medium

6.2.1 Winds

These galaxies are young relative to the age of the Universe at the epoch they are observed ($\sim 1.2$ Gyr at the median redshift). The young ages derived for the majority of $z \sim 5$ LBGs imply that these systems began appreciable star formation at $z \sim 6$ with the bulk of their stars formed at $z < 6$. As such, if reionization was complete at $z \sim 5.8$ (Becker et al. 2001; Fan et al. 2001), the intense star formation episode studied here could only significantly contribute to the end of reionization and these galaxies are unlikely to be the perpetrators. However, these young galaxies do have an impact on the high-redshift IGM. These compact galaxies are experiencing widespread and recent star formation at prodigious rates. The UV emitting regions are small ($\sim 1$ kpc) and consequently these $z \sim 5$ LBGs have high rest-frame UV surface brightnesses. Given the typical SFRs inferred from the SED modelling, their SFR surface densities (SFR per unit area) are several tens to hundreds $M_\odot$ yr$^{-1}$ kpc$^{-2}$. This is far higher than observed SFR surface densities of local galaxies that are known to be driving vigorous gaseous outflows ($>0.1 M_\odot$ yr$^{-1}$ kpc$^{-2}$; Heckman 2001). Thus, young $z \sim 5$ galaxies host strong outflows, expelling the metals created by stellar nucleosynthesis into the surrounding medium. As such, these vigorous starbursts must contribute to the early chemical enrichment of the IGM which is supported by the detection of ions of metals such as Carbon in the IGM at redshifts as high as $\sim 5$ (Songaila 2005 and references therein).

6.2.2 Galaxy-scale metal-mixing and Population III star formation

The first stars in the Universe must have been born from gas of primordial abundance (so-called Population III stars). Recent detections of the signatures of Population III stars in the composite spectrum of $z \sim 3$–4 LBGs suggest that such a population comprises 10–30 per cent of the stellar mass, implying that galaxy-wide mixing of metals is inefficient on time-scales of a billion years (Jimenez & Haiman 2006). Most models of galaxy formation have assumed efficient intragalactic mixing of metals and do not predict metal-free star formation at redshifts significantly below $z \sim 5$ (Yoshida et al. 2004). While the star formation intensities suggest that our young galaxies are likely to drive outflows and pollute the IGM with metals, and presumably their own interstellar media, their very young ages imply that this material does not reach far beyond galactic scales. We can quantify this statement by making some simple assumptions about the outflows driven by these high intensity star-forming galaxies in analogy with local starburst galaxies.

The temperature of the outflowing gas can be estimated by simple energetic arguments (i.e. energy injected rate of the intense star formation equals the rate at which material – both ambient and stellar ejecta – is thermalized; Moran, Lehnert & Helfand 1999; Heckman 2001)

$$T_{\text{wind}} \approx 0.4 m_f \frac{E}{k M} = 5.4 \times 10^5 \frac{E_{43}}{M_{10}} f^{-1}_{\text{loading}} \text{K},$$

(2)

where $m_f$ is the mass of hydrogen, $E$ is the energy injection rate, and $M$ is the mass outflow rate, $k$ is Boltzmann’s constant, and $f_{\text{loading}}$ is the fraction of hot gas that results from ‘mass loading’ due to sweeping up and entraining ambient interstellar material. Using the models of Leitherer et al. (1999), at the median age and SFRs we have estimated form fits to the SEDs of the robust sample of LBGs, the typical energy and mass injection rates are about $10^{43}$ergs$^{-1}$ ($E_{43}$) and about $10 \ M_\odot$ yr$^{-1}$ ($M_{10}$), respectively, to which we have scaled equation (2).

Similarly, equating the kinetic energy of the gas to the energy injection rate yields an estimate of the outflow velocity:

$$v_{\text{wind}} = \left( \frac{2 E}{M} \right)^{1/2} \sim 1800 f^{-1/2}_{\text{loading}} \left( \frac{E_{43}}{M_{10}} \right)^{1/2} \text{km s}^{-1}.$$  

(3)

The mass loading of local starburst winds has been estimated to be about a factor of a few to 10 (Moran et al. 1999). This would decrease the wind velocity accordingly. If we assume that winds are loaded by a factor of 5, then the wind velocity is $\sim 800 \text{ km s}^{-1}$. In the typical age of the LBGs, the wind would traverse $\sim 15$ kpc. Therefore, in principal, it is possible for the wind to span and enrich the ambient interstellar medium with metals. However, we have assumed that the mass loading is a simple drain on the energy of the wind material itself. In reality, the ambient ISM will be an inhomogeneous medium with clumps of higher density material. The diffuse ISM will get swept up while the clouds will be entrained and accelerated by the ram pressure of the wind material itself. In such a situation, it is important to consider both how a continuous medium and clouds are accelerated in the outflowing gas. Following, for example, Dyson & Williams (1980), expansion speed of the shell and energy content of the bubble are related as

$$v_{\text{shell}} \sim 240 E_{43}^{1/5} n_0^{-1/5} t_f^{-2/5} \text{km s}^{-1}.$$  

(4)

where $E_{43}$ is the (constant) energy injection rate in units of $10^{43}$ erg s$^{-1}$, $n_0 = 1.0 \text{ cm}^{-3}$ is the ambient ISM density in cm$^{-3}$ and $t_f$ is the injection time in units of 10 Myr. At such velocities, swept-up ambient ISM will traverse about 5 kpc over the age of the typical LBG in our sample. Clouds accelerated in the wind will be

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8 Our assumed $0.2 Z_\odot$ corresponds very well to the combined $Z \sim 0$ and $0.4 Z_\odot$ mixed model of Jimenez & Haiman (2006).
dispersed over a similar size scale. Since this is only a factor of a few larger than the half light radii of the galaxies in our sample, given the strong collimation of superwinds observed in the local Universe (e.g. Heckman, Armus & Miley 1990; Lehnert & Heckman 1996), it is unlikely that the metals in the outflow will be mixed significantly with the infalling or ambient gas.

While even the swept-up ambient ISM is unlikely to be efficiently mixed by the pressure and outflow of the intense star formation, another interesting time-scale to investigate is the cooling time of the hot superwind gas. If the gas were to have a long cooling time, then it would be unavailable for star formation. This would effectively sequester the metal enriched gas from the stellar mass-loss from being incorporated into star formation over a cooling time-scale. We estimated previously that the wind material itself, modulo the mass loading, will have a temperature of $\approx 5 \times 10^7$ K. This plasma will also be very rare. We can crudely estimate the density of the gas using the relationship from Chevalier & Clegg (1985), namely,

$$n_{\text{e, wind}} \approx M_{\text{w}} \frac{10^{0.5}}{R} R^{-2},$$

where we have scaled the radius to 1 kpc, $R_{1\text{kpc}}$, approximately the half-light radius of the typical LBG in our sample and the area over which energy is being injected by massive stars. If the wind that has reached large distances from the LBG is mass loaded, the density will be of course higher (likely be a factor of a few to 30). The various ranges of density, depending on radius and mass loading will be of the order of $10^{-2}$ to $10^{-4}$, similar to what has been estimated in local starburst galaxies. Using this crude estimate, we can investigate the likely cooling time of the wind using standard cooling arguments. For an equilibrium plasma at a temperature of $10^{6.5}$ to $10^{7.5}$ K and density of $10^{-2}$ to $10^{-4}$, the cooling time is, roughly $10^8$ yr to a few $\times 10^9$ yr. Over that duration, the star formation will be able to build up about 10–30 per cent of the mass of LBGs at $z \sim 3$ and so with much of the metals generated by the intense star formation at higher redshifts locked in hot gas that takes about 1 Gyr to cool. Of course, the velocities estimated are also to likely be approximately or greater than the escape velocities of the dark matter haloes and much of the enriched material may escape. These tight timing constraints are consistent with evidence of both a significant fraction of Population III stars in lower redshift LBGs and inefficient metal-mixing on intragalactic and intergalactic scales (Jimenez & Haiman 2006).

7 SUMMARY

We present the properties of a robust sample of LBGs at $z \sim 5$ selected to $I_{\text{AB}} < 26.3$ in the CDF-S. On average, LBGs at $z \sim 5$ are $\sim 10$ times less massive ($\sim 10^9 M_\odot$) and are significantly younger ($<100$ Myr) than similarly luminous LBGs at $z \sim 3$. While LBGs with such low masses and young ages are not uncommon at $z \sim 3$ they are far less common, such systems comprise $\sim 70$ per cent of LBGs at $z \sim 5$ and in contrast only $\sim 30$ per cent at $z \sim 3$. Their short duty cycles suggest that the $z \sim 5$ population must be highly stochastic and that samples of $z \sim 5$ LBGs may be highly incomplete, with only $\sim 1$-in-$13$ LBGs being detected. Considering this implies that up to $\sim 1$ per cent of the present-day stellar mass density can be accounted for by luminous LBGs (cf. 15 per cent a Gyr later; Rudnick et al. 2006). The abundant fraction of young and moderately massive $z \sim 5$ LBGs are likely to be experiencing their first (few) generations of large-scale star formation and are accumulating their first significant stellar mass. Their formation redshifts ($z \sim 6–7$) suggests these galaxies could have contributed only to the end of reionization. They are extremely compact as measured from the UV ACS images ($r_{1/2} \sim 1$ kpc) giving rise to high stellar mass and SFR surface densities. The stellar mass surface densities and core phase-space densities are comparable to the spheroidal components of present-day L* galaxies and suggests these systems are the progenitors of early-type galaxies or bulges, favouring the inside-out galaxy formation scenario. The high SFR surface densities imply these sources are driving winds that enrich the intergalactic and intragalactic media with metals. Their young ages are consistent with inefficient metal-mixing on galaxy-wide scales. Therefore it is plausible that these galaxies contain a significant fraction of Population III stars as has been proposed for $z \sim 3$ LBGs.

ACKNOWLEDGMENTS

We would like to thank the anonymous referee for their constructive and insightful comments that substantially improved this paper. We thank Matthias Tecza and Elizabeth Stanway for their comments and useful discussion. Some of the data presented in this paper were obtained from the Multidisciplinary Archive at the Space Telescope Science Institute (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. This work is based (in part) on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA. We acknowledge the ESO/GOODS EIS and spectroscopy projects (13,17) which have been carried out using the Very Large Telescope at the ESO Paranal Observatory under Program IDs LP170.A-0788 and LP168.A-0485.

REFERENCES

Bouwens R. J., Illingworth G. D., 2006, Nat, 443, 189

APPENDIX A: ALTERNATIVE MODELLING ASSUMPTIONS

To assess the sensitivity of our characteristic ensemble properties to the model assumptions, we fit the SEDs of the $z \sim 5$ LBGs with different sets of input parameters, varying the SFH, extinction law and metallicity. As we are interested in the ensemble properties, we focus on the effects of variations on the median properties of the robust sample of $z \sim 5$ LBGs. Degeneracies between the model parameters make it difficult to discriminate between SFHs, extinction laws or metallicities based solely on the reduced chi-squared values ($\chi^2_r$). One must also keep in mind that there are uncertainties in the stellar evolution, spectral libraries, and dust properties themselves, especially important at sub-Magellanic metallicities (see the discussion by Bruzual & Charlot 2003) as well as regarding their validity at $z \sim 5$. Differences in goodness-of-fit, even systematic, may reflect in part template mismatches.

We discuss the effects of varying the assumed parameters in the following subsections and Table A1 summarizes some of the key variations. However, in view of all the uncertainties involved, the numbers quoted in the following should not be taken at face value but rather as indications of overall trends. The interloper fraction (low-$z$ galaxies as well as QSOs) for the initial sample of 109 candidate $z \sim 5$ LBGs is roughly 40 per cent in all cases; the median $z_{ph}$ for the robust sample is around 4.8 except for dust-free models with star formation time-scales longer than $\sim 50$ Myr, for which it increases by about 0.2. Only models without dust extinction could affect our conclusion of young ages and could make the ensemble as old or older than $\sim 100$ Myr. However, such models are also those that lead to the poorest fits compared to any other set of input parameters, although they cannot be ruled out from a purely statistical $\chi^2$ argument. Typical stellar masses for the ensemble of a few $\times 10^9 M_\odot$ are derived for all but the lowest metallicities explored, $Z = 0.002$–0.02 $Z_\odot$.

A1 Star formation history

In addition to our adopted constant SFR (CSF) scenario, we considered a suite of exponentially declining SFRs with e-folding time-scales $\tau$ of 10, 30, 50, 100, 300, 500 Myr and 1 Gyr, as well as the case of a single stellar population (SSP) formed in an instantaneous burst.

Adopting the $0.2 Z_\odot$ models and the SMC extinction law, the median best-fitting age is a few tens of Myr, for all SFHs except for the SSP where it decreases by a factor of $\approx 2$. This behaviour is not surprising given the degeneracies between age and SFH: the best-fitting age gives a measure of the time elapsed since the bulk of stars that dominate the observed SED was formed, so the derived ages tend to be younger for models with shorter star formation time-scales. Since most of the LBGs in the robust sample have ages of a few tens of Myr, any SFH with time-scale of that order or longer is effectively equivalent to a CSF model and the derived ages are similar. The best-fitting extinction changes little, with median $A_V$ values of a few tenths of magnitude for $\tau \gtrsim 30$ Myr down to 0 mag for shorter time-scales. The median SFR decreases by a very modest $\approx 10$ per cent between CSF and $\tau = 30$ Myr models, and drops by a factor of 2 for $\tau = 10$ Myr (by definition, there is no star formation for a SSP with non-zero age). The median stellar mass shows no systematic variations and remains roughly constant with star formation time-scale, the largest difference amounting to $\approx 17$ per cent, smaller than the dispersion among individual objects in the sample.

The trends of lower median best-fitting ages, $A_V$ values, and SFRs with star formation time-scales are qualitatively the same irrespective of the metallicity or extinction law. The exception is the median age for dust-free $0.002 Z_\odot$ models, which increases from 3 Myr for all SFHs to 6 Myr for an SSP; this difference is however at the limit of the age sampling in our modelling and is not very significant. The median SFRs drop by $\approx 15$ per cent up to a factor of $\approx 5$ from CSF to $\tau = 10$ Myr models, depending on the metallicity and extinction law. For the stellar masses, the median values vary by a factor of 1.5 or less between different SFHs for any given metallicity and extinction law considered, and up to a factor of 1.8 for models without dust extinction.

A2 Extinction Law

Our choice of an SMC-type extinction law was motivated by consistency with the adopted metallicity of $Z = 0.2 Z_\odot$. Assuming the starburst extinction law of Calzetti et al. (2000, hereafter Calzetti law) instead, which is widely applied in high-redshift studies, the median best-fitting $A_V$ values increase by a large amount up to about 1.2 mag (0.6 mag for an SSP) and at the same time, extremely young median ages of only a few Myr are derived. The Calzetti law is much greyer (i.e. shallower) in the rest-frame UV than the SMC law, so that higher levels of extinction are allowed but this then requires

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variation</th>
<th>SFR (M$_\odot$ yr$^{-1}$)</th>
<th>Mass (M$_\odot$)</th>
<th>Age (Myr)</th>
<th>$A_V$ (mag)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CSF</td>
<td>few $\times$ 10</td>
<td>$2 \times 10^6$</td>
<td>few $\times$ 10</td>
<td>few $\times 10^{-1}$</td>
</tr>
<tr>
<td></td>
<td>exp. declining $\tau &gt; 30$</td>
<td>~ few $\times$ 10</td>
<td>$2 \times 10^9$</td>
<td>few $\times$ 10</td>
<td>few $\times 10^{-1}$</td>
</tr>
<tr>
<td></td>
<td>exp. declining $\tau &lt; 30$</td>
<td>10</td>
<td>$2 \times 10^9$</td>
<td>few $\times$ 10</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>SSP</td>
<td>~</td>
<td>$2 \times 10^9$</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Extinction law</td>
<td>SMC</td>
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<td>$2 \times 10^9$</td>
<td>few $\times$ 10</td>
<td>few $\times 10^{-1}$</td>
</tr>
<tr>
<td></td>
<td>Calzetti extinction law</td>
<td>few to several $\times 10^{5–3}$</td>
<td>$5 \times 10^9$</td>
<td>few</td>
<td>1–2</td>
</tr>
<tr>
<td>Metallicity</td>
<td>1 $Z_\odot$</td>
<td>few $\times$ 10</td>
<td>$5 \times 10^9$</td>
<td>200</td>
<td>1–2</td>
</tr>
<tr>
<td></td>
<td>0.2 or 0.4 $Z_\odot$</td>
<td>few $\times$ 10$^2$</td>
<td>$2 \times 10^9$</td>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>0.002 or 0.02 $Z_\odot$</td>
<td>few $\times$ 10</td>
<td>$1 \times 10^9$</td>
<td>few tens</td>
<td>few $\times 10^{-1}$</td>
</tr>
</tbody>
</table>

For $0.2 Z_\odot$ templates and the SMC extinction law.
younger ages to fit the very blue SEDs of our LBG sample. As a consequence of the younger ages and higher $A_v$ values, both the median stellar mass and SFR increase, by factors of 2–3 and 30–60, respectively.

The properties and geometry of interstellar dust at $z \sim 5$ is currently an open issue, and the application of extinction laws derived for low-redshift galaxies to high-redshift systems is questionable. Low to moderate extinction would be expected for young systems in which it would be unlikely that significant amounts of widespread dust have had sufficient time to form. Moreover, the detection of Lyz in the spectrum of some of these systems argues against strong attenuation by dust. There is empirical evidence that dust in $z \sim 2–4$ LBGs exhibits SMC-like characteristics (Vijh, Witt & Gordon 2003). At higher $z$ and given the young ages inferred for our LBG sample, it may be that dust from Type II supernovae dominates the extinction, as proposed for $z \sim 6$ quasars by Maiolino et al. (2004).

However, in the absence of determinations valid for star formation dominated $z \sim 5$ LBGs, the SMC extinction law is a reasonable assumption. It also leads to modest extinction, older ages, and lower SFRs that are more plausible than the extremely young ages of a few Myr, and the high $A_v \sim 1$ mag and SFRs $\sim 1000 M_\odot \ yr^{-1}$ obtained with the Calzetti extinction law.

Models where we allowed extinction to be a free parameter fit the data better than models without attenuation by dust, even though the required best-fitting extinction is modest for our adopted metallicity and SMC extinction law ($A_v \sim 0.3$ mag). This is reflected in the overall systematically higher $\chi^2$ values for the zero-extinction case. Strictly speaking, the differences are not statistically significant so that models without dust extinction cannot be conclusively excluded. However, given that there is spectroscopic evidence that the metallicity of LBGs is $0.2 Z_\odot$ (Ando et al. 2004), a dust-free solution is highly unlikely.

**APPENDIX B: LIMITS ON THE CONTRIBUTION OF AN OLD POPULATION**

The SEDs of all our $z \sim 5$ LBGs are very blue in the rest-frame UV, indicating the presence of ongoing or very recent star formation. The best-fitting stellar masses (like all other derived properties) represent those of the young and luminous populations that dominate the integrated rest-frame UV to near-infrared light. By selection, we would not expect to have picked up old passively evolving galaxies. Therefore it is unlikely that these luminous LBGs contain a significant, older, less luminous component that significantly contributes to the stellar mass. Moreover, the $z \sim 5$ LBGs in our sample are extremely compact in the GOODS-ACS data ($r_{1/2} \sim 1$ kpc), and given that they are selected at an $i$-band magnitude significantly brighter than the depth of these images, any old stellar population would have to follow an extremely broad distribution to remain undetected. If any significant old population is distributed over the same extent as the UV luminous galaxy, then this would imply an extremely high-mass surface density ($\gtrsim 10^{10} M_\odot \ kpc^{-2}$), in place already at $z \sim 5$. Such high-mass surface densities are known only in the inner regions ($\lesssim kpc$-scale) of massive cD galaxies, and they are not for typical starburst galaxies or $z \sim 3$ LBGs. This unlikely high surface density strongly argues against a significant fraction of old stars contributing to the galaxy mass, and suggests that the stellar mass derived from the stellar synthesis modelling is representative of the total mass of the galaxy.

Nevertheless, we can place extreme upper limits on the mass contribution of such an old underlying population following a similar procedure to that used for LBGs at $z \sim 3$ (Papovich et al. 2001; Shapley et al. 2001, 2005). This consistent approach allows us to test whether such an old contribution can explain the mass difference we have found which has been discussed in Section 5. For this we consider an extreme ‘worst case’ scenario, requiring the coincidence of a SSP which, compared to scenarios of extended star formation, maximizes the mass-to-light ratio of a ‘hidden’ component for a given age. For this we assume the true photometry of the source is in fact at the brightest $1\sigma$ limit of our photometric uncertainties. These uncertainties already include a generous 10 per cent to account for flux calibration errors. Therefore, the limit that results is extreme and while there is a chance that it can apply to an individual source, it is highly unlikely to be valid for the population as a whole.

We consider the case of a passively evolving component with an age of 500 Myr, the median for the one-third of our robust sample older than 100 Myr, and comparable to the oldest ages for $z \sim 5$ LBGs reported by other authors as well (e.g. Eyles et al. 2005; Yan et al. 2006b). The SED of a 500-Myr-old SSP peaks in the rest-frame optical, in particular just redwards of the Balmer/4000 Å break, and so would contribute most to the observed fluxes in the $K_s$, 3.6 and 4.5-$\mu$m bands. We thus determined the upper limit for an old component by adding to the nominal best-fitting SED for each object the maximum contribution from a 500-Myr-old SSP allowed by the $1\sigma$ uncertainties on the $K_s$, 3.6- and 4.5-$\mu$m photometric points. The typical maximum contribution corresponds to an increase in flux by a factor of 2.5 and translates into a factor of $\approx 7$ times more stellar mass.$^9$

However, this factor must not be taken at face value. The assumption of a 500 Myr to maximally old passively evolving population

$^9$ The additional flux of this old component to the other bands always remains within the $1\sigma$ uncertainties of the photometry. At observed wavelengths bluer than $K_s$, the light contribution of the old component becomes much smaller relative to the strong rest-frame UV emission from the young stars. Compared to the 3.6- and 4.5-$\mu$m data, the 5.8- and 8-$\mu$m photometry does not provide useful limits because of significantly lower sensitivity and larger uncertainties.

formed in an instantaneous burst, made to maximize the mass-to-light ratio, is more extreme than any detected population. Any scenario with an old component that has been forming stars for some non-negligible period of time, even if short, will reduce this upper limit. And considering our conservative photometric uncertainties, an upper limit to the mass contributions for our $z \sim 5$ LBGs will be considerably less than this. Similar factors have been determined for $z \sim 3$ LBGs (3–5 Papovich et al. 2001; Shapley et al. 2001), and therefore such a potential contribution from old stars would be insufficient to make the mass ranges shown in Section 5 of the sample overlap.

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