The discovery of a significant sample of massive galaxies at redshifts $5 < z < 6$ in the UKIDSS Ultra Deep Survey early data release

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Accepted 2006 July 25. Received 2006 July 14; in original form 2006 June 7

ABSTRACT
We have exploited the large area coverage of the combined UKIDSS Ultra Deep Survey (UDS) and Subaru/XMM–Newton Deep Survey (SXDS) to search for bright Lyman-break galaxies (LBGs) at $z \geq 5$. Using the available optical + near-infrared photometry to efficiently exclude low-redshift contaminants, we identify nine $z \geq 5$ LBG candidates brighter than $z'_{AB} = 25$ within the 0.6-deg$^2$ overlap region between the UDS early data release and the optical coverage of the SXDS. Accounting for selection incompleteness, we estimate the corresponding surface density of $z \geq 5$ LBGs with $z'_{AB} \leq 25$ to be 0.005 ± 0.002 arcmin$^{-2}$. Modelling of the optical + near-infrared photometry constrains the candidates’ redshifts to lie in the range 5.1 $< z < 5.9$, and provides estimates for their stellar masses. Although the stellar mass estimates are individually uncertain, a stacking analysis suggests that the typical stellar mass of the LBG candidates is $\geq 5 \times 10^{10}$ M$_\odot$ which, if confirmed, places them amongst the most massive galaxies currently known at $z \geq 5$. It is found that Lambda cold dark matter structure formation can produce sufficient numbers of dark matter haloes at $z \geq 5$ to accommodate our estimated number density of massive LBGs for plausible values of $\sigma_8$ and the ratio of stellar to dark matter. Moreover, it is found that recent galaxy formation models can also account for the existence of such massive galaxies at $z \geq 5$. Finally, no evidence is found for the existence of LBGs with stellar masses in excess of $\simeq 3 \times 10^{11}$ M$_\odot$ at this epoch, despite the large comoving volume surveyed.

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

1 INTRODUCTION
The increasing availability of survey fields with deep multiwave-length data has led to so-called ‘dropout’ techniques becoming established for photometrically identifying high-redshift galaxies. At redshifts of $z \geq 6$ it is now standard practice to select galaxy candidates using the i-drop technique, a straightforward extension of the Lyman-break method pioneered at $z \simeq 3$ by Guhathakurta, Tyson & Majewski (1990) and Steidel & Hamilton (1992). Within this context, the unique combination of depth and image quality provided by the Hubble Space Telescope (HST) has arguably made the largest contribution to our understanding of high-redshift galaxies. Analysis of the Hubble deep fields, the GOODS fields, and in particular the Hubble ultradepth field (HUDF), has led to the identification of hundreds of i-drop galaxy candidates at faint ($z_{580} > 26.1$) magnitude (e.g. Bunker et al. 2004; Dickinson et al. 2004; Malhotra et al. 2005; Bouwens et al. 2006). As a consequence, we now have a vastly improved understanding of the galaxies which undoubtedly dominate the star formation density of the Universe during the epoch immediately following re-ionization.
However, although HST has greatly advanced our knowledge of high-redshift galaxies, the various HST deep fields suffer from one fundamental weakness. Crucially, their small area (e.g. the HUDF covers \( \simeq 13 \) arcmin\(^2\)) makes them subject to significant cosmic variance (Somerville et al. 2004) and completely unsuitable for investigating the most luminous, rarest objects. Indeed, of the many hundreds of \( i \)-drop galaxies identified in the deep HST fields, only one has \( z > 5 \) (SBM03#3, spectroscopically confirmed at \( z = 5.78 \); Bunker et al. 2003). This is an important circumstance because accurately determining the number density of massive galaxies at high redshift (\( z > 5 \)) has the potential to place important new constraints on galaxy formation models, only 1 Gyr after the Big Bang. From an observational perspective, it is clear that what is required is a combination of both depth and large area coverage.

In this respect, the study of \( z \simeq 6 \) LBGs in the Subaru Deep Field (SDF; Maihara et al. 2001) by Shimasaku et al. (2005) is perhaps the most notable. Based on deep Subaru optical imaging covering 767 arcmin\(^2\), Shimasaku et al. (2005) identified 12 bright LBGs with \( z \)-band magnitudes in the range 25.4 \( < z < 26.6 \), photometrically selected to lie in the redshift range 5.6 \( < z < 6.2 \). Moreover, by using two medium-band filters (\( z_{SB} \) and \( z_{SB} \)) which divide the Subaru \( z \)-prime filter in half, Shimasaku et al. (2005) gained crucial information on the UV slope of their high-redshift candidates. As a consequence, Shimasaku et al. (2005) were able to select a very clean sample, which should have negligible contamination from low-redshift interlopers. In addition, Ota et al. (2005) performed a search for \( z \leq 26 \) LBGs over a sky area of \( \sim 1 \) deg\(^2\) in the SXDS field, using a primary selection criterion of \( i - z > 1.5 \). However, Ota et al. (2005) were only able to strongly constrain the surface density of LBG candidates at \( z > 25 \), because at brighter magnitudes their lack of near-infrared data made it impossible to exclude significant contamination from low-redshift interlopers, and cool galactic stars in particular. Finally, it should be noted that there is already evidence for a large population of \( z \simeq 6 \) galaxies at fainter \( z \)-band magnitudes within the SXDS/UDS field. Using a combination of the broad \( i \)-band SXDS imaging and a narrow-band filter (\( \lambda = 8150 \) \( \AA \)), Ouchi et al. (2005) identified 515 potential Ly\( \alpha \) emitters (LAEs) within the redshift interval 5.65 \( < z < 5.75 \), over an area of 1 deg\(^2\). Further deep optical spectroscopy subsequently confirmed eight LAEs at \( z \simeq 5.7 \) with asymmetric Ly\( \alpha \) emission lines. However, the LAEs detected by Ouchi et al. (2005) are fainter (\( z > 25 \)) than the objects identified in this study (and presumably have lower mass).

In this paper we exploit two crucial advantages of the combined SXDS/UDS data set to explore a new area of LBG parameter space at \( z \geq 5 \). First, the overlap region between the SXDS and the UDS early data release (EDR) is \( \geq 2.5 \) times larger than the SDF (\( \geq 0.6 \) deg\(^2\)), offering the prospect of identifying the rarest \( z \geq 5 \) LBGs with \( z \leq 5 \). Secondly, the near-infrared data from the UDS EDR allows us to effectively clean the sample of low-redshift contaminants, and to obtain stellar mass estimates for the LBG candidates. The structure of the paper is as follows. In Section 2 we give a brief review of the optical and near-infrared data currently available in the SXDS/UDS field. In Section 3 we outline the criteria adopted for selecting the \( 5 < z < 6 \) galaxy candidates, and discuss the possible sources of contamination. In Section 4 we present the results of our modelling of the spectral energy distributions (SEDs) of the candidates. In Section 5 we estimate the number densities of massive LBGs at \( z \geq 5 \) and compare with the predictions of current galaxy formation models. In Section 6 we compare our results with those in the recent literature, before presenting our conclusions in Section 7. Throughout the paper we adopt the following cosmology:

\[
H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}, \quad \Omega_m = 0.3, \quad \Omega_{\Lambda} = 0.7.
\]

When referring to the \( i \) and \( z \)-band filters, \( i' \) and \( z' \) specifically refer to the Subaru filters, whereas \( i_{614} \) and \( z_{580} \) are the equivalent HST filters.

2 THE DATA

In this paper we identify potential massive galaxies at high redshift by combining optical data from the Subaru telescope with near-infrared data from the UK Infrared Telescope (UKIRT). The optical data were taken as part of the Subaru/XMM–Newton Deep Survey (Sekiguchi et al. 2005) while the near-infrared data has been taken from the EDR (Dye et al. 2006) of the UKIRT Infrared Deep Sky Survey (Lawrence et al. 2006). The properties of both data sets are briefly outlined below.

2.1 The Subaru/XMM–Newton deep survey

The Subaru/XMM–Newton Deep survey (SXDS) primarily consists of optical and X-ray imaging covering an area of \( \simeq 1.3 \) deg\(^2\), centred on right ascension (RA) = 02:18:00, declination (Dec.) = \(-05:00:00 \) (J2000). In addition, the SXDS field has IRAC and MIPS data from the Spitzer SWIRE survey (Lonsdale et al. 2003), deep 1.4 GHz radio observations from the VLA (Simpson et al. 2006a) and 850-micron sub-mm observations from SCUBA (Mortier et al. 2005). Of primary concern for this study is the deep optical imaging of the field undertaken with Suprime-Cam (Miyazaki et al. 2002) on Subaru. The optical imaging consists of five overlapping Suprime-Cam pointings, and covers an area of \( \simeq 1.3 \) deg\(^2\). The whole field has been in the \( BVRiz' \) filters, to typical 5\( \sigma \) depths of \( B = 27.5, V = 26.7, R = 27.0, i' = 26.8 \) and \( z' = 25.9 \) (2 arcsec diameter apertures).

2.2 The UKIDSS Ultra Deep Survey

The Ultra Deep Survey (UDS) is one of five near-infrared surveys being undertaken with WFCAM (Casali et al. in preparation) on UKIRT, which together comprise the UKIRT Infrared Deep Sky Survey (UKIDSS). The UDS will take seven years to complete, and will provide ultradeep \( JHK \) imaging of a 0.8-deg\(^2\) area (centred on the SXDS field), to 5\( \sigma \) point-source limits of \( J = 26.0, H = 25.4 \) and \( K = 25.0 \). The UDS EDR consists of the first 12 h of \( \text{JK} \) imaging data and reaches 5\( \sigma \) limits of \( J = 22.5 \) and \( K = 22.5 \) within a 2 arcsec diameter aperture. For this paper we have used an improved version of stacking and catalogue extraction constructed by the current authors, rather than the default version in the WFCAM Science Archive. This will be described in Foucaud et al. (2006). The authors of this paper are also members of the UKIDSS consortium, so we intend that our improved stacking and source extraction will be made available to help to develop the final WSA data base. Due to a small change in the UDS field centre shortly after the beginning of the survey, the current \( \text{JK} \) imaging is not uniform over the entire 0.8-deg\(^2\) field. Consequently, for the purposes of this paper, we restrict our analysis to the 0.6 deg\(^2\) central region which has uniform \( \text{JK} \) data and optical Subaru coverage.

3 HIGH-REDSHIFT CANDIDATE SELECTION

Our sample of bright LBGs at \( z \geq 5 \) was initially selected from the Subaru optical imaging, followed by SED fitting of the Subaru + UDS data to isolate robust candidates. The optical selection criteria were as follows:
Table 1. Names, optical positions and 2 arcsec diameter aperture photometry for the final nine high-redshift LBG candidates (quoted limits are 1σ). The consistent image quality of the optical + near-infrared data (0.7 < FWHM < 0.8 arcsec) means that differential aperture corrections between bands are small (≤0.1 mag). All aperture magnitudes have been confirmed manually to check for errors in the original catalogue photometry. Four objects (MCD2, MCD5, MCD6 and MCD9) have photometry calculated in a 1.6 arcsec diameter aperture to avoid possible contamination from nearby sources (as a result we note that formally MCD9 has a colour of $R - z' = 2.90 ± 0.27$, rather than $R - z' ≥ 3.0$). Although the majority of the aperture photometry in the $i'$ and $z'$ filters has $S/N ≥ 10$, a minimum error of 0.1 mag was adopted during the SED fitting process to account for possible zero-point errors.

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<td>$&gt;28.40$</td>
<td>$&gt;28.70$</td>
<td>$27.33 ± 0.31$</td>
<td>$24.63 ± 0.07$</td>
<td>$&gt;24.28$</td>
<td>$24.22 ± 0.73$</td>
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<td>$&gt;29.49$</td>
<td>$&gt;28.64$</td>
<td>$28.92 ± 0.74$</td>
<td>$26.31 ± 0.11$</td>
<td>$25.04 ± 0.08$</td>
<td>$24.20 ± 0.60$</td>
<td>$23.99 ± 0.52$</td>
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<td>-04:56:59.3</td>
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<td>$&gt;28.40$</td>
<td>$&gt;28.70$</td>
<td>$26.15 ± 0.11$</td>
<td>$24.63 ± 0.07$</td>
<td>$23.71 ± 0.51$</td>
<td>$23.37 ± 0.39$</td>
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<td>$&gt;28.40$</td>
<td>$&gt;28.70$</td>
<td>$26.09 ± 0.10$</td>
<td>$24.63 ± 0.07$</td>
<td>$&gt;24.28$</td>
<td>$23.68 ± 0.50$</td>
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<td>$&gt;29.49$</td>
<td>$&gt;28.64$</td>
<td>$&gt;28.94$</td>
<td>$26.35 ± 0.11$</td>
<td>$25.00 ± 0.07$</td>
<td>$24.15 ± 0.58$</td>
<td>$23.53 ± 0.37$</td>
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<td>$&gt;28.40$</td>
<td>$28.38 ± 0.60$</td>
<td>$25.40 ± 0.06$</td>
<td>$24.25 ± 0.05$</td>
<td>$23.89 ± 0.57$</td>
<td>$23.99 ± 0.62$</td>
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<td>$&gt;28.40$</td>
<td>$&gt;28.70$</td>
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<td>$24.64 ± 0.07$</td>
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<td>$23.17 ± 0.34$</td>
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<td>$&gt;28.64$</td>
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<td>$25.39 ± 0.05$</td>
<td>$24.36 ± 0.04$</td>
<td>$&gt;24.52$</td>
<td>$&gt;24.51$</td>
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<td>-04:47:55.2</td>
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<td>$&gt;28.64$</td>
<td>$27.52 ± 0.26$</td>
<td>$25.67 ± 0.06$</td>
<td>$24.62 ± 0.05$</td>
<td>$23.92 ± 0.49$</td>
<td>$23.91 ± 0.49$</td>
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(i) $z' ≤ 25$,
(ii) non-detection (<2σ) in the $B$ and $V$ bands,
(iii) $R - z' ≥ 3$.

The magnitude cut at $z' ≤ 25$ was chosen to fully exploit the area of the UDS, and to isolate the most luminous/massive $z ≥ 5$ galaxies which cannot be studied using smaller area surveys. Furthermore, from a practical point of view, for objects with $z ≥ 25$ the shape of the SED longward of the $z'$ band cannot be properly constrained (with the early-release UDS data), making it impossible to identify robust candidates (see Section 3.2). The requirements for non-detections in the $B$ and $V$ bands, together with a red $R - z' ≥ 3$ colour, are designed to ensure our selection function has a sharp low-redshift cut-off at $z = 5$. At $z ≥ 5$ both the $B$- and $V$-band sample rest-frame wavelengths shortward of Ly$\alpha$, and any genuine high-redshift LBGs should not be detected at >2σ significance in these bands. Moreover, in the redshift interval $5 < z < 6$ the Subaru $R$ and $z'$-filters bracket the onset of absorption by the Ly$\alpha$ forest, and simulations demonstrate that a colour cut of $R - z' ≥ 3$ effectively excludes galaxies at $z < 5$. Finally, it should be noted that during the optical selection process we did not actually impose the standard $i'$-drop criterion. The reason for this is that the standard colour cut (i.e. $i'_{14} - z'_{580} > 1.3$; Bunker et al. 2004) can exclude galaxies in the redshift range $5.0 < z < 5.5$. In contrast, for the purposes of this study, we are interested in including all possible candidates at $z ≥ 5$, which is better achieved using the $R - z' ≥ 3$ colour cut. However, as can be seen from Table 1, all of the final nine LBG candidates satisfy $i' - z' ≥ 1.0$, fully consistent with the expected colours of $z ≥ 5$ LBGs in the Subaru filter set.

3.1 Optical + near-infrared model fitting

Following the application of the initial optical selection criteria, the next step in the selection process was to analyse each potential candidate with our template-fitting photometric redshift code (Cirasuolo et al. in preparation), which is largely based on the public package HYPERZ (Bolzonella, Miralles & Pelló 2000). The photometric redshift for each galaxy is computed by fitting the observed multiband $(BVRIcz'JK)$ photometry with synthetic galaxy templates. We adopt the stellar population synthesis models of Bruzual & Charlot (2003) for the galaxy templates, assuming a Salpeter initial mass function (IMF) with a lower and upper mass cut-off of 0.1 and 100 $M_\odot$, respectively. Both instantaneous burst and exponentially declining star formation models – with e-folding times in the range $0.1 ≤ \tau (\text{Gyr}) ≤ 15$ – were included, all with fixed solar metallicity. The code accounts for dust reddening by following the Calzetti et al. (2000) obscuration law within the range $0 < A_V < 10$, and accounts for Lyman series absorption due to the H$\text{I}$ clouds in the intergalactic medium according to the Madau (1995) prescription. In addition to the best-fitting photometric redshift, the code also returns best-fitting values for: SED type, age, mass and reddening.

In addition to providing redshift and stellar mass estimates, the principle reason for performing the optical + near-infrared SED fits was to clean the sample of low-redshift interlopers. A simple application of the optical selection criteria described above produced an initial sample of 74 candidates. By making full use of the extra information provided by the near-infrared UDS data, 65 members of this initial sample were eventually excluded as low-redshift contaminants. The names, positions and photometry for the final nine LBG candidates are listed in Table 1, and the fits to their optical + near-infrared photometry are shown in Fig. 1. In the next section we discuss in detail the potential sources of contamination, and the strategies adopted for excluding them from the final sample.

3.2 Sources of contamination

In the current study there are three types of contaminants which are of potential concern: ultracool galactic stars (M, L or T dwarfs), extremely red objects (EROs) at $z ≃ 1$ and high-redshift quasars. It is important to develop strategies for excluding these contaminants based on their optical + near-infrared SEDs because, unlike previous HST studies, ground-based resolution makes it impossible to exclude stellar and QSO contaminants on the basis of being spatially unresolved.

3.2.1 Ultracool galactic stars

Due to the ≥0.8 arcsec full width at half-maximum (FWHM) resolution of the available ground-based imaging of the SXDS/UDS field, high-redshift LBGs are expected to be unresolved point sources. Consequently, the prospect of significant contamination of the final sample by ultracool galactic stars is potentially serious. Ultracool galactic stars (M, L or T dwarfs) perfectly mimic the redshifted SEDs of $z ≥ 5$ LBGs in the optical (Hewett et al. 2006), and would certainly pass our initial optical selection criteria. Consequently, in
In order to exclude stellar contaminants it is necessary to rely on the fact that ultracool galactic stars exhibit redder $z' - J$ colours than genuine $z \geq 5$ LBGs. To quantify this we used the library of spectra maintained by Sandy Leggett\textsuperscript{2} to calculate the likely colours of M, L and T dwarfs in the Suprime-Cam + WFCAM filter set. This process revealed that we could efficiently exclude the cooler L and T dwarfs from the final sample by rejecting any potential candidate which was detected in the UDS EDR $J$-band imaging at $\geq 2\sigma$ significance. This is because the red $z' - J \geq 1.5$ colours typical of L and T dwarfs means that, at $z' \leq 25$, they should be significant ($\geq 3\sigma$) detections in the EDR $J$-band imaging. However, unfortunately the potential for contamination by M dwarfs is much more significant. Due to the fact that none of the final nine LBG candidates are formally detected in the $J$ band (all $<2\sigma$ detections), the limits on their $z' - J$ colours are typically $z' - J \leq 1.0$, compatible with those of M dwarfs with $i' - z' \geq 1.0$. To tackle this issue, as part of the SED fitting we used the available M dwarf spectra (spectral types M1 to M9) as templates to fit the LBG candidates’ photometry. For seven of the nine final candidates, using galaxy templates

\textsuperscript{2}www.jach.hawaii.edu/skl
3.2.2 Stacking analysis

In order to confirm that the final sample of nine LBG candidates is not heavily contaminated by M dwarf stars, we stacked (averaged) the images of the final nine candidates in all available bands. Postage stamp images centred on the stack of all nine high-redshift LBG candidates in the $BVRIz'JK$ and 3.6-μm Spitzer bands are shown in Fig. 2, and the SED fit to the stacked photometry is shown in Fig. 3.

Several points regarding the stacked image and accompanying SED fit are noteworthy. First, due to the extra ≳ 1 magnitude in depth achieved by stacking, it is possible to confirm that the average SED of the final candidates is robustly undetected in the bluest optical bands to 2σ limits of $B = 29.5$ and $V = 28.7$. Second, the colours of the LBG stack are $i' – z' = 1.28 \pm 0.14$ and $z' – J = 0.22 \pm 0.35$. An M dwarf star with $i' – z' = 1.3$ is expected to have $z' – J \simeq 1.0$, significantly redder than the $z' – J$ colour of the LBG stack. This alone is enough to strongly suggest that the final candidate list is not heavily contaminated by M dwarfs, and is confirmed by the fact that the best fit to the stacked $BVRIz'JK$ photometry using an M dwarf template can be confidently excluded ($\Delta \chi^2 = 25$). Moreover, although each of the final nine candidates is

Table 2. The best-fitting parameters from the optical + near-infrared SED fitting. Columns list the name, SED template, $\chi^2$, primary redshift solution, 1σ redshift range, extinction, age, stellar mass and allowed stellar mass range (see text for discussion). Although a wide range of different star formation histories were considered, in all cases the best-fitting SED template was either 1 = instantaneous burst or 2 = exponential decay model (e-folding time $\tau = 0.3$ Gyr). The photometry for the two objects highlighted with a * symbol can be fitted with an M dwarf stellar template with a comparable $\chi^2$, and these objects cannot be firmly ruled out as possible stellar contaminants.

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<th>SED</th>
<th>$\chi^2$</th>
<th>$z$</th>
<th>$\Delta z$</th>
<th>$A_v$</th>
<th>Age (Myr$^{-1}$)</th>
<th>$\log (M/M_\odot)$</th>
<th>$\Delta M$</th>
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<td>2.6</td>
<td>5.85</td>
<td>$5.76 &lt; z &lt; 6.20$</td>
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<td>57</td>
<td>10.3</td>
<td>10.3 &lt; $M &lt; 10.8$</td>
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<td>1*</td>
<td>2.5</td>
<td>5.38</td>
<td>$5.08 &lt; z &lt; 5.56$</td>
<td>0.8</td>
<td>57</td>
<td>10.8</td>
<td>10.3 &lt; $M &lt; 10.9$</td>
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<td>5.47</td>
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<td>1.0</td>
<td>57</td>
<td>11.2</td>
<td>10.6 &lt; $M &lt; 11.3$</td>
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<td>5.29</td>
<td>$5.16 &lt; z &lt; 5.54$</td>
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<td>509</td>
<td>11.2</td>
<td>10.6 &lt; $M &lt; 11.5$</td>
</tr>
</tbody>
</table>

Figure 2. $BVRIz'JK$ and 3.6-μm postage stamp images of the stacked data for all nine of the final high-redshift LBG candidates. Each stamp is 20 arcsec$^2$ (except the 3.6-μm stamp, which is 10 arcsec$^2$), and is displayed using a grey-scale which is a linear stretch ±3σ around the mean sky level. The name of the filter is shown in the bottom left-hand corner of each stamp, and the position of the stacked LBG candidate is highlighted using an arrow.

Produced significantly better fits to the LBG photometry (Table 2) than could be achieved with the M dwarf templates. However, for two of the final candidates (MCD2 and MCD3) the M dwarf SED fits were of comparable quality to those achieved with $z > 5$ galaxy templates. Consequently, it remains possible that these two objects are M dwarf contaminants. However, we have chosen to keep them in the final sample because $z > 5$ LBG templates provide a very good fit to their photometry and, even including these two objects, a stacking analysis suggests the final candidate list of nine objects is not heavily contaminated by M dwarf stars.
individually undetected in the 3.6-µm SWIRE data, the stack does provide a marginal \( \approx 1.5\sigma \) detection \((m_{1.6} = 24.0 \pm 0.5)\), entirely consistent with a prediction based on the individual SED fits shown in Fig. 1. Crucially, if the final candidate list consisted largely of ultracool galactic stars, there would be no detection at 3.6 µm.

There is one final comparison which can be performed using the stacked data to provide further information on the reliability of our selection technique. As previously mentioned, in the GOODS CDFS field there is one bright \( z \gtrsim 5 \) LBG known with \( z_{\text{spec}} \leq 25 \) (SBM03#03), spectroscopically confirmed to be at \( z = 5.78 \) by Bunker et al. (2003). This object is the only high-redshift LBG within the deep \( HST \) survey fields which is comparable in brightness to the candidates selected here. In the right-hand panel of Fig. 3 we show the photometry for this object, together with our SED fit. Reassuringly, our SED fit accurately recovers the spectroscopic redshift \( z_{\text{spec}} = 5.7 \pm 0.1 \) using best-fitting model parameters very similar to those required to fit the photometry of our nine high-redshift LBG candidates. Moreover, it can clearly been seen from Fig. 3 that the SEDs of SBM03#03 and our LBG stack are very similar, providing additional evidence that our final candidate list is robust.

### 3.2.3 Extremely red objects

Based solely on our optical selection criteria, contamination of the final sample by EROs at \( z \approx 1 \) is possible if the 4000-Å break is confused with the Lyman break. However, given the extra information from the UDS EDR near-infrared data, we can be confident that ERO contamination is not an issue. As can be seen from Fig. 1, none of the final nine candidates displays a significant degeneracy between plausible solutions at low and high redshift. Although an alternative photometric redshift solution at \( z \approx 1 \) inevitably exists for each candidate, in every case the low-redshift solution can be excluded at \( \approx 99.9 \) per cent confidence \((\Delta \chi^2 \gtrsim 18)\). This is confirmed by our SED fit to the stacked LBG photometry (Fig. 3) which shows the ERO solution at \( z \approx 1 \) to be completely unacceptable \((\Delta \chi^2 = 75)\). This clear separation between high- and low-redshift solutions is particularly notable given that during the SED fitting process, extreme values of intrinsic reddening \((0 < A_V < 10)\) were fully explored.

From a more empirical perspective, we have also investigated the potential for contamination using a sample of 3715 \( R - K \gtrsim 5.3 \) (Vega) EROs with a \( K\)-band limit of \( K_{\text{lim}} \leq 22.2 \), selected from the same data set as our LBG candidates (Simpson et al. 2006b). Within this sample there are 2140 EROs with photometric redshifts in the range \( 0.8 < z < 1.4 \) and \( z \leq 25 \). As expected, none of these EROs display a statistically acceptable photometric redshift solution at \( z \gtrsim 5 \). The fundamental reason for this is that none of them have the blue SED slope longward of the \( R' \) band displayed by our final \( z \gtrsim 5 \) LBG candidates. Perhaps the most convincing evidence for this comes from the SED of the stacked photometry of all nine \( z \gtrsim 5 \) LBG candidates (Figs 2 and 3), which has a colour of \( z' - K = 0.73 \pm 0.25 \). For comparison, the average \( z' - K \) colour of \( z \approx 1 \) EROs in the UDS field is \( z' - K = 2.32 \pm 0.32 \) (where the quoted uncertainty is the standard deviation).

### 3.2.4 High-redshift quasars

High-redshift quasars in the redshift range \( 5.0 < z < 6.5 \) have predicted \( i' - z' \) and \( z' - J \) colours which are comparable with those of our final nine LBG candidates (Willott et al. 2005). However, none of the final candidates are detected in the deep 0.2–12 keV band X-ray imaging of the SXDS with \( XMM-Newt\). The sensitivity of the \( XMM-Newt \) SXDS observations varies somewhat over the SXDS field, but the typical X-ray flux upper limits imply X-ray luminosity limits of \( \lesssim (5-10) \times 10^{44} \text{ erg s}^{-1} \) (rest-frame energy band \( \approx 1-70 \text{ keV} \)). Moreover, based on the latest constraints on the QSO
luminosity function at \( z \approx 6 \) (Willott et al. 2005), contamination of our sample from high-redshift QSOs is expected to be minimal (conservatively \( \leq 1 \) QSO is anticipated with \( z' < 25 \) over the SXDS/UDS field).

### 3.2.5 Lensing

Finally, given that we have deliberately selected the brightest objects of their type at \( z \geq 5 \), it is important to at least consider the possibility that some of the final LBG candidates may be lensed. The first scenario to consider is the prospect of moderate amplification due to a lensing geometry where the LBG candidates lie outside the Einstein radii of lensing objects along the line of sight. If we model the potential lens as a single isothermal sphere, then the amplification is \( \mu = \theta/(\theta - \theta_\text{E}) \), where \( \theta_\text{E} \) is the Einstein radius \( \theta_\text{E} = 4\pi(\sigma_v/c)^2 D_\text{LS}/D_S \), \( \sigma_v \) is the velocity dispersion of the lensing galaxy, \( D_S \) is the angular diameter distance of the source and \( D_\text{LS} \) is the angular diameter distance of the source from the lens. Four of the final nine LBG candidates have nearby companions within 2.5 arcsec of the line of sight, which could potentially produce amplification via lensing. To investigate this we have estimated the velocity dispersions and consequent amplification for these objects, using their photometric redshifts and the \( M_\text{L} - \sigma_v \) correlation at \( z \approx 0 \) from Bernardi et al. (2003). This calculation reveals that none of the companion objects are compatible with having \( \sigma_v \geq 100 \text{ km s}^{-1} \), and that any amplification from lensing is therefore small (i.e. \( \mu \ll 1 \)).

The second scenario to consider is the prospect of high amplification due to extremely close alignment along the line of sight between the LBG candidates and potential lensing objects in the foreground. Although difficult to rule out completely, the remarkably clean nature of the LBG candidates’ optical photometry suggests that it is quite unlikely. For the \( z \geq 5 \) LBG candidates the largest cross-section for lensing occurs at \( z \approx 0.8 \). Consequently, if we consider an \( L_\star \) elliptical at \( z = 0.8 \) as the potential lens, we can predict that it would have apparent magnitudes of \( K \approx 19.9, V \approx 25.5 \) and \( B \approx 26.6 \) (assuming \( M_\star^* = -22.9; \) Pozzetti et al. 2003). These magnitudes are completely incompatible with those of the stack of the final nine LBG candidates, which is undetected to 2\sigma limits of \( B = 29.5 \) and \( V = 28.7 \), and has a \( K \)-band magnitude of \( K = 23.86 \pm 0.23 \). Consequently, the average luminosity of any potential lensing objects would have to be \( < 0.03L_\star \) to avoid detection in the stacked photometry, which leads us to conclude that the probability of lensing is negligible.

### 3.2.6 Colour–colour selection

Finally, for completeness, in Fig. 4 we show the location of the final nine high-redshift LBG candidates on the \( R - z' \) versus \( z' - J \) colour–colour plane. Also shown in Fig. 4 is the locus of M, L and T dwarfs and those EROs from Simpson et al. (2006b) which satisfy our selection criteria of being undetected in the \( B \) and \( V \) bands, and have \( z' \)-band magnitudes in the same range as the LBG candidates (\( 24 < z' < 25 \)). Although Fig. 4 suggests that traditional colour–colour selection based on \( R - z' \geq 3 \) and \( z' - J \leq 1 \) would successful isolate our high-redshift LBG candidates from low-redshift EROs, it also illustrates the potential for contamination by M dwarf stars (as discussed in Section 3.2.1). However, once again, the location of the stacked LBG photometry on the \( R - z' \) versus \( z' - J \) plane strongly suggests that the final LBG candidate list is not significantly contaminated by low-redshift interlopers. For the purposes of obtaining a robust sample of high-redshift LBG candidates, Fig. 4 further emphasizes the importance of modelling the full \( BV R'z'JK \) SEDs, using both galaxy and stellar templates, rather than relying on simple colour–colour selection.

### 4 MODELLING RESULTS

In Table 2 we list the best-fitting galaxy template parameters resulting from the optical + near-infrared SED fits to each of the final nine high-redshift LBG candidates (as illustrated in Fig. 1). All of the candidates have best-fitting photometric redshifts in the range \( 5.1 < z < 5.9 \), validating our original selection criteria. Moreover, as previously discussed, none of the candidates displays a plausible low-redshift solution, despite the fact that an extreme range of intrinsic reddening (\( 0 < A_V < 10 \)) was explored during the SED fitting process. This is potentially crucial because, as highlighted by Dunlop, Cirasuolo & McLure (2006), it is possible to confuse extremely dusty (\( A_V \geq 4 \)) low-redshift objects with genuine high-redshift galaxies if the range of reddening explored is constrained to moderate values (e.g. \( A_V \leq 2 \)).

#### 4.1 Ages and reddening

Although the age of the Universe at \( z \approx 5 \) (1.1 Gyr) was not used as a prior in the model fitting, reassuringly the best-fitting ages for all the final nine candidates naturally satisfy this constraint, and are consistent with formation redshifts in the range \( 5.6 < z_{\text{for}} < 9.0 \). As is expected given the LBG selection criteria, there is no evidence in our sample for substantial amounts of reddening. Indeed, the range of reddening displayed by our sample (\( 0 < A_V < 1 \)) is perfectly consistent with that found for LBGs at \( z \approx 3 \) by Shapley et al. (2001).
4.2 Stellar masses

By concentrating exclusively on the brightest (z’ ≤ 25) candidates, this study was designed to investigate the most massive LBGs at z ≥ 5. The success of this policy can be seen from Table 2, which shows that six of the nine final candidates have estimated stellar masses \( \geq 5 \times 10^{10} \, M_\odot \) and five have estimated masses \( \geq 10^{11} \, M_\odot \). If these stellar mass estimates are accurate, then the LBG candidates are among the most massive galaxies yet discovered at these redshifts (see discussion in Section 5), and are comparable to the highest stellar masses found for LBGs at z ≥ 3 by Shapley et al. (2001), who also adopted a Salpeter IMF. In fact, these stellar mass estimates suggest that several of the z ≥ 5 LBG candidates have already built-up a stellar mass comparable with \( M^*_{\text{min}} \), today \( \approx 10^{11} \, M_\odot \) Col et al. 2001).

However, given the current depth of the near-infrared data from the UDS EDR, and the fact that the SWIRE data covering the UDS field is not deep enough to individually detect the LBG candidates, it is clear that on an object-by-object basis the stellar mass estimates must be regarded with some caution. The first issue to consider is the range of stellar masses which are allowable within the SED templates we have adopted to fit the optical + near-infrared photometry. By identifying the SED templates with the lowest and highest masses which still provide a statistically acceptable fit to the observed photometry (conservatively \( \Delta \chi^2 \leq 10 \), marginalized over all other free parameters), we have calculated the allowable stellar mass range for each of the LBG candidates (Table 2). This calculation reveals that the photometry of most of the LBG candidates can be acceptably reproduced (although with a worse \( \chi^2 \)) by SED templates with a factor of \( \geq 3 \) less stellar mass.

In addition, there is also the added uncertainty introduced by the choice of a specific IMF. For the SED fits presented in this paper we have made the standard choice of adopting a Salpeter IMF, for ease of comparison with previous results in the literature. However, it is widely recognized that the Salpeter IMF results in higher stellar mass estimates than other popular choices. For example, refitting the LBG optical + near-infrared photometry with a Kennicutt or Chabrier IMF would produce stellar mass estimates a factor of \( \approx 1.5 \) lower. In conclusion, it is clear that the individual stellar mass estimates for the LBG candidates are very likely uncertain to within a factor of \( \geq 5 \).

In order to obtain a more robust estimate of the typical mass of the z ≥ 5 LBGs, we have also calculated stellar mass estimates based on the stacked LBG photometry. The obvious advantage of this is that the extra depth provided by stacking produces much more robust photometry in the J and K bands, and also provides a detection at 3.6 \( \mu \)m from the stacked SWIRE data. Using a straightforward average stack of the LBG data (see Figs 2 and 3) our SED fit returns a stellar mass estimate of \( \approx 5 \times 10^{10} \, M_\odot \). However, this stack is biased due to the inclusion of the two LBG candidates with the lowest stellar mass estimates (MCD1 & MCD8), which have the faintest detections in both the B and V bands, data, using the \( \chi^2 \) band as the detection image. This revealed that the photometry of most of the LBG candidates can be acceptably reproduced (although with a worse \( \chi^2 \)) by SED templates with a factor of \( \geq 3 \) less stellar mass.

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5 MASSIVE GALAXIES AT HIGH REDSHIFT

The results presented in the previous section suggest that, despite the considerable uncertainties, the typical stellar mass of the z ≥ 5 LBG candidates is \( \geq 5 \times 10^{10} \, M_\odot \). In this section we investigate whether the existence of such massive galaxies at this early epoch is consistent with Lambda cold dark matter (ΛCDM) structure formation and current galaxy formation models. Within this section we adopt the best-fitting stellar mass estimates for each LBG candidate, based on a Salpeter IMF. However, when necessary, we adjust our estimated number densities to account for differences due to specific choices of IMF.

5.1 Surface density

The first, model-independent, quantity of interest to calculate is the surface density of z ≤ 25 galaxies at z ≥ 5. However, in order to accurately compute the surface density, it is first necessary to account for the inevitable incompleteness introduced during the construction of the original SEXTRACTOR (Bertin & Arnouts 1996) catalogues due to object blending. To quantify this effect we performed simulations based on introducing 1000 fake LBG candidates at a time into the z’-band images, and attempting to recover them using the same SEXTRACTOR configuration adopted for constructing the original z’-band catalogues. This immediately revealed that on average we lose \( \approx 10 \) per cent of possible LBG candidates due to object blending on the z’-band images. In addition, we then proceeded to run SEXTRACTOR in two-image mode on the corresponding B- and V-band data, using the z’-band as the detection image. This revealed that we lose further LBG candidates due to contamination of the matched apertures in the B and V bands by nearby companions. In around \( \approx 5 \) per cent of cases this contamination is sufficient to fail our selection criteria requiring \( \approx 2 \sigma \) detections in both the B and V bands.

Consequently, when calculating the surface density of z ≤ 25 LBGs it is necessary to scale-up by a factor of \( \approx 1.2 \). Allowing for this correction factor, our estimate for the surface density of z ≤ 25 LBGs at z ≥ 5 is 0.005 \( \pm \) 0.002 arcmin^{-2}. We note that this figure is compatible with, although obviously much more robust than, a prediction based on the one previously known z ≥ 5 LBG with \( z_{\text{iso}} \leq 25 \) in a compilation of deep HST survey fields; 0.004 \( \pm \) 0.004 arcmin^{-2} (Bouwens et al. 2006). We also note that our final list of nine z’ ≤ 25 LBGs at z ≥ 5 is fully consistent with the previous findings of Shimasaku et al. (2005) in the SDF. Within the 767-arcmin^2 area of the SDF, Shimasaku et al. (2005) did not find any possible z’ ≤ 25 LBGs, but did identify 12 candidates in the magnitude range 25.4 < z’ < 26.6. However, it is important to remember that the selection technique adopted by Shimasaku et al. (2005) was tuned to identify LBGs in the redshift interval 5.6 < z < 6.2. Only one of our final lists of nine candidates lies within this redshift range (MCD1). Consequently, based on our final sample, we would predict only \( \approx 0.4 \) LBG candidates with z’ ≤ 25 within the SDF area which would satisfy the Shimasaku et al. (2005) selection criteria, entirely consistent with their finding of none.

5.2 Number densities

The best-fitting stellar mass estimates listed in Table 2 suggest that five of the LBG candidates have masses of M ≥ 10^{11} M_\odot. In order to convert the estimated surface density of M ≥ 10^{11} M_\odot LBGs at z ≥ 5 into a number density, it is necessary to compute the effective comoving volume of our survey (defined by the survey area and the redshift intervals within which each of the LBG candidates could have been detected; z_{\text{min}} < z < z_{\text{max}}). Due to our adopted optical selection criteria, our selection function has a sharp low-redshift cut-off at z_{\text{min}} = 5. To compute z_{\text{max}} we have taken the SED fit to...
each candidate and redshift it (keeping age, reddening and mass constant) until the candidate fades below our magnitude limit (z' = 25). This calculation reveals that, for the five LBG candidates with M ≥ 10^{11} M_☉, the effective volume of the survey is equivalent to the full comoving volume covered by our 0.6-deg^2 area over the redshift interval 5.0 < z < 5.6 (i.e. 3.3 × 10^{6} Mpc^3).

5.2.1 Completeness

Additionally, in order to calculate a meaningful estimate of the number density of M ≥ 10^{11} M_☉ LBGs in our sample, it is also necessary to estimate our completeness as a function of stellar mass. To investigate this we produced simulated photometry for 10,000 LBGs with parameters randomly selected from uniform distributions with the following ranges:

(i) stellar masses: 10^{10} M_☉ < M < 10^{12} M_☉,
(ii) ages: 50 Myr < age < 500 Myr,
(iii) extinction: 0.0 < A_V < 1.0,

where the adopted parameter ranges are based on the results of the SED fits presented in Table 2, and are also consistent (in terms of ages) with recent results suggesting that re-ionization occurred in the redshift interval 6 < z < 10 (Fan et al. 2006; Page et al. 2006). The simulated LBG catalogue was then subjected to the same optical and near-infrared selection criteria adopted for the real data set (see Section 3). In Fig. 5 we show the resulting estimate for sample completeness as a function of stellar mass. It can be seen from this figure that for LBGs with stellar masses of ∼10^{11} M_☉ we are only ≃40 per cent complete. Consequently, to calculate our final estimate of the number density of M ≥ 10^{11} M_☉ LBGs within our sample we are required to correct the observed numbers by a factor of ∼2.5. Taking this correction into account, our final estimate for the number density of M ≥ 10^{11} M_☉ LBGs at z ≥ 5 is log (φ/Mpc^{-3}) = −5.2^{+0.3}_{−0.3}, where the quoted error includes a 20 per cent contribution from cosmic variance (Somerville et al. 2004), but does not include possible systematics in the adopted completeness correction. If, in reality, LBG candidate MCD3 is an M dwarf contaminant, then the estimate number density would be ∼20 per cent lower.

5.3 Comparison with dark matter halo number densities

The most fundamental test which we can perform is to ask whether ΛCDM produces the required number of dark matter haloes to host galaxies with stellar masses of ∼10^{11} M_☉ at this early epoch. In order to explore this issue we have calculated the number density of dark matter haloes as a function of redshift predicted by the Press–Schechter formalism (Bond et al. 1991). In Fig. 6 we show the redshift evolution of the dark matter halo number density for haloes more massive than 1.5 × 10^{12} M_☉, which corresponds to a stellar to dark matter ratio of 15. Although the typical stellar to dark matter ratio of massive galaxies as a function of redshift is not accurately known, our choice of 15 as a representative figure is motivated by several lines of reasoning. First, assuming a halo occupation number of unity, the predicted number density of M_{DM} ≥ 1.5 × 10^{12} M_☉ dark matter haloes at z = 0 is in good agreement with the locally observed number density of galaxies with stellar masses ≥10^{11} M_☉ (Salpeter IMF; Cole et al. 2001). Moreover, a ratio between halo mass and stellar mass of ∼15 at low redshift is in good agreement with recent galaxy–galaxy lensing results (Mandelbaum et al. 2006). Finally, at high redshift, a stellar to dark matter ratio of ∼15 is also in agreement with the predictions of recent galaxy formation models (R. Bower, private communication). At high redshift the number density of dark matter haloes is strongly dependent on the value of the σ_s parameter. Consequently, in Fig. 6 we show the dark matter halo number density evolution for four different values of σ_s (0.90, 0.85, 0.80 and 0.75). The final value of σ_s = 0.75 is in agreement with the Wilkinson Microwave Anisotropy Probe 3-yr results (Spergel et al. 2006).

In Fig. 6 we also plot our estimated number density of LBGs with stellar masses ≥10^{11} M_☉ from this study (median z = 5.3). It can be seen from Fig. 6 that, assuming a stellar to dark matter ratio of 15, ΛCDM does produce sufficient haloes at high redshift to host our LBG candidates provided σ_s ≥ 0.8. In fact, given the large uncertainties associated with our estimated number density, our results

3Using code kindly provided by Will Percival.
are also fully consistent with the latest determination of $\sigma_8 = 0.75$. Consequently, we can conclude that our estimated number density of massive galaxies at $z \geq 5$ can certainly be accommodated within current ΛCDM models of structure formation.

Furthermore, it has recently been suggested that $\simeq 60$ per cent of the stellar mass at $z \simeq 5$ is missed by traditional dropout selection techniques (Stark et al. 2006), which exclude high-redshift galaxies which are too red in the rest-frame optical to satisfy LBG selection criteria (see discussion in Section 6). However, even if we increase our estimated number density of massive galaxies at $z \simeq 5$ by a factor of 2, and assume $\sigma_8 = 0.75$, ΛCDM can still produce the required number of dark matter haloes if the stellar to dark matter ratio is $\simeq 10$.

In Fig. 6 we also show the estimated number densities of $\geq 10^{11} M_\odot$ galaxies at $z \leq 3$ derived from a K-band selected sample of galaxies in the GOODS CDFS (Caputi et al. 2006). The Caputi et al. (2006) sample has a magnitude limit of $K \leq 23.3$, and is $\geq 85$ per cent complete for stellar masses $\geq 10^{11} M_\odot$ (Salpeter IMF) at redshifts $z \leq 3$. As can be seen from Fig. 6, the conclusions of Caputi et al. (2006) were that $\simeq 20$ per cent of the local mass density comprised by galaxies with stellar masses $\geq 10^{11} M_\odot$ was already in place by $z \simeq 2$, and that the majority was in place by $z \simeq 1$. Similar conclusions have been reached by numerous studies of deep, small area, near-infrared surveys (e.g. Drory et al. 2005; Fontana et al. 2004). The results presented here strongly suggest that the increase in number density of massive galaxies within the redshift interval $2.5 < z < 5.5$ closely traces the build-up of suitable dark matter haloes and that, as a consequence, only $\lesssim 1$ per cent of the local density of $\geq 10^{11} M_\odot$ galaxies was in place by $z \simeq 5$.

5.4 Comparison with galaxy formation models

It has recently become apparent that the number density of massive, red galaxies observed at high redshift is much larger than would have been predicted by semi-analytic galaxy formation models five years ago (e.g. Cimatti et al. 2002; Glazebrook et al. 2004). In essence this is simply a result of the fact that galaxy formation models based on hierarchical assembly naturally produce the most massive galaxies at late times. This apparent discrepancy between the models and observations has been described variously as ‘anti-hierarchical’ behaviour, or cosmic downsizing. It is clear therefore that important constraints can be placed on the latest generation of galaxy formation models via comparison with the observed number density of massive galaxies already in place at $z \geq 5$.

In Fig. 7 we show the predicted number density of galaxies as a function of stellar mass at $z = 5.3$ (median redshift of our LBG candidates) from the latest generation of Durham semi-analytic galaxy formation models, which incorporate active galactic nucleus (AGN) feedback (Bower et al. 2006). Also shown in Fig. 7 are the predictions (G. L. Granato, private communication) from the latest version of the Durham semi-analytic galaxy formation model, which incorporates AGN feedback (Bower et al. 2006). The filled circle is our estimate of the number density of massive galaxies within a bin centred on $10^{11} M_\odot$, based on the results of this study. When plotting the data point in Fig. 7, we have shifted the centre of the bin to lower mass by 0.15 dex, to account for the difference between the Salpeter IMF adopted in this paper, and the IMFs adopted in the Bower et al. (2006) and Granato et al. (2004) models (Kennicutt and Romano et al. 2002, respectively). As can be seen from Fig. 7, our estimated number density is clearly in good agreement with the predictions of the Bower et al. (2006) and Granato et al. (2004) models. Interestingly, given that our number density is almost certainly a lower limit, both model predictions can accommodate a number density which is a factor of $\simeq 2–3$ higher than our estimate, as required if LBGs constitute $\lesssim 50$ per cent of the total stellar mass at $z \geq 5$ (e.g. Stark et al. 2006). Finally, although not included in Fig. 7, we also note that our estimated number density of $z \leq 25$ LBGs at $z \geq 5$ is fully consistent with the hydrodynamical simulations of Night et al. (2006).

6 Comparison with recent results

In this study we have exploited the large comoving volume covered by the SXDS/UDS data set to identify a sample of bright ($z' \leq 25$) LBGs at $z \geq 5$. In this section we compare our results with those of three recent studies based on the extensive multiwavelength data available in the GOODS CDFS (Grazian et al. 2006; Stark et al. 2006; Yan et al. 2006).

The GOODS MUSIC sample (Grazian et al. 2006) consists of z- and K-band selected samples in the southern GOODS field, and provides a photometric redshift for each object calculated from SED fits to the extensive, high-quality, HST + VLT + Spitzer imaging available in the field. The z-band catalogue is 100 per cent complete to $z_{500} = 25$ and, although it only covers 142 arcmin$^2$, it is obviously of some interest to compare the number of $z \geq 5$ galaxies found in the MUSIC sample to the results presented here. Based on the results of this study, and correcting for the difference in area, the number of $z_{500} \leq 25$ LBG-type galaxies within the GOODS MUSIC catalogue should be consistent with 0.73 $\pm$ 0.30. Interestingly, the GOODS MUSIC catalogue contains seven objects with $z_{500} \leq 25$ and a photometric redshift estimate of $z \geq 5$, seemingly very inconsistent with the results presented here. However, our own SED fits to the MUSIC photometry for these seven objects suggest that only two are believable high-redshift candidates.

Three of the seven objects (MUSIC IDs 1133, 8316 and 12966) have SEDs which are clearly stellar in nature, and have SExtractor stellarity parameters of 0.98, 0.99 and 0.99, respectively. In addition, MUSIC ID 7004 has a clear V-band detection which is inconsistent with the best-fitting photometric redshift of $z_{\text{phot}} = 6.91$. Finally, MUSIC ID 10140 has a very unusual SED which would appear to
be due to severe blending with bright nearby objects in the near-infrared and Spitzer bands. Of the original seven objects, this leaves two apparently robust candidates with $z_{\text{phot}} \leq 25$ (MUSIC IDs 499 and 3094). One of these (MUSIC ID 499) is the spectroscopically confirmed LBG SBFM30#003 (Bunker et al. 2003) and the other (MUSIC ID 3094) has been spectroscopically confirmed at $z \equiv 5.55$ by the GOODS VLT spectroscopy campaign (Vanzella et al. 2006). Consequently, given that the GOODS MUSIC catalogue is complete to $z_{\text{phot}} = 25$ (i.e. does not employ any colour selection), and the much larger cosmic variance in the smaller GOODS field ($\pm 40$ per cent; Somerville et al. 2004), we conclude that the number of robust galaxies with $z_{\text{phot}} \leq 25$ in the MUSIC catalogue is in good agreement with the results presented here.

In their recent study, Stark et al. (2006) assemble a combined photometric and spectroscopic catalogue of objects in the GOODS CDFS field to investigate the stellar mass density at $z \simeq 5$. Within their sample Stark et al. (2006) have two objects with $z \geq 5$ and $z_{\text{phot}} \leq 25$, one with a spectroscopic redshift of $z = 5.55$ (MUSIC ID 3094) and the other with a photometric redshift of $z_{\text{phot}} = 5.38$ (also from the MUSIC catalogue). Our SED fits to these two objects successfully reproduce the redshift of the spectroscopically confirmed candidate, but are unable to produce a statistically acceptable high-redshift fit to the candidate with $z_{\text{phot}} = 5.38$. Consequently, if we also include SBFM30#003 ($z_{\text{spec}} = 5.78$; Bunker et al. 2003), we again conclude that the GOODS CDFS field contains two $z \geq 5$ objects with $z_{\text{phot}} \leq 25$.

Interestingly, the $z_{\text{spec}} = 5.55$ object in the Stark et al. (2006) sample is not a classic i-drop ($\Delta H_\alpha - z_{\text{phot}} = 0.57$) and would not have passed our strict selection criteria (estimated colour $R - z = 2.1$ in the Subaru filters). This has two consequences. First, it brings the observed number of $z \geq 5$ LBGs in the GOODS CDFS field with $z_{\text{phot}} \leq 25$ into good agreement with the results presented here, which correspond to 0.73 $\pm$ 0.30 objects per GOODS CDFS area. Secondly, it provides further evidence for the conclusion of Stark et al. (2006) that traditional dropout selection techniques are missing $\geq 60$ per cent of the stellar mass at $z \leq 5$. Finally, Yan et al. (2006) have recently completed a study of the stellar mass density at $z \simeq 6$ based on a i-drop selection of galaxies in the north and south GOODS fields (combined area $\simeq 330$ arcmin$^2$). Within their sample, Yan et al. (2006) find two objects at $z \geq 5$ with $z_{\text{phot}} \leq 25$. This is in good agreement with the results presented in this paper, which correspond to 1.69 $\pm$ 0.56 objects per GOODS field (N + S).

6.1 The absence of supermassive galaxies

As a final comment we note here that we have found no evidence in this study for the existence of LBGs with masses in excess of $3 \times 10^{11}$ M$_\odot$ in the redshift interval $5 < z < 6$. Although still uncertain, this non-detection is notable given that we should be $\geq 60$ per cent complete to LBG-type objects of this mass (see Fig. 5) over a volume of $\geq 5 \times 10^6$ Mpc$^3$. Consequently, the detection of even one object of this mass within the UDS/SXDS field would have pointed to a number density of $\log (\dot{\phi}/$Mpc$^{-3}) \simeq -6.7$. Our non-detection is in agreement with the recent search for $\geq 3 \times 10^{11}$ M$_\odot$ galaxies within the GOODS CDFS field by Dunlop et al. (2006).

7 CONCLUSIONS

In this paper we have presented the results of a study aimed at exploiting the large comoving volume of the SXDS/UDS data set to identify the most massive LBGs at $z \geq 5$. Our main conclusions can be summarized as follows.

(i) We have identified a robust sample of nine bright ($z' < 25$) LBG candidates with photometric redshifts in the range $5.1 < z < 5.9$.

(ii) Our corresponding estimate of the surface density for $z < 25$ LBGs at $z \geq 5$ is $0.005 \pm 0.002$ arcmin$^{-2}$. This surface density estimate is in good agreement with, although much more robust than, a prediction based on the one previously known LBG candidate with $z_{\text{phot}} \leq 25$ in a compilation of the deep HST fields; 0.044 $\pm 0.004$ arcmin$^{-2}$ (Bouwens et al. 2006).

(iii) SED fits to the stacked photometry of the final nine LBG candidates suggests that their typical stellar mass is $\geq 5 \times 10^{10}$ M$_\odot$ (Salpeter IMF), comparable with the most massive galaxies currently known at $z \geq 5$.

(iv) Based on our best-fitting stellar mass estimates, five of the nine LBG candidates have estimated stellar masses $\geq 10^{11}$ M$_\odot$. Our corresponding estimate for the number density of $z \geq 5$ LBGs with stellar masses $\geq 10^{11}$ M$_\odot$ is $\log (\phi/Mpc^{-3}) = -5.2+0.2$.

(v) This number density is found to be compatible with the density of suitable dark matter haloes predicted by $\Lambda$CDM structure formation models for plausible combinations of $\sigma_8$ and the ratio of stellar to dark matter.

(vi) It is found that recent galaxy formation models can account for the existence of such massive galaxies at high redshift, even if LBGs only account for $\leq 50$ per cent of the total stellar mass at $z \geq 5$.

(vii) Despite the large comoving volume surveyed, no evidence is found for the existence of LBGs with masses in excess of $3 \times 10^{11}$ M$_\odot$ at $z \geq 5$.

ACKNOWLEDGMENTS

The authors would like to acknowledge Richard Bower and Gian Luigi Granato for providing their stellar mass function predictions. The authors would also like to acknowledge Nigel Hamblly and Niall Deacon for useful discussions on the nature of cool galactic stars and Will Percival for providing the code to calculate halo number densities. RJM, OA and IS would like to acknowledge the funding and Will Percival for providing the code to calculate halo number densities. RJM, OA and IS would like to acknowledge the funding of the Royal Society. MC, SF and CS would like to acknowledge funding from PPARC. We are grateful to the staff at UKIRT and Subaru for making these observations possible. We also acknowledge the Cambridge Astronomical Survey Unit and the Wide Field Astronomy Unit in Edinburgh for processing the UKIDSS data.

REFERENCES

Glazebrook K. et al., 2004, Nat, 430, 181
Miyazaki S. et al., 2002, PASJ, 54, 833
Ota K., Kashikawa N., Nakajima T., Iye M., 2005, JKAS, 38, 179
Sekiguchi K. et al., 2005, in Renzini A., Bender R., eds, Multiwavelength Mapping of Galaxy Formation and Evolution. Springer-Verlag, Berlin, p. 82

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