GALEX-SELECTED LYMAN BREAK GALAXIES AT z ∼ 2: COMPARISON WITH OTHER POPULATIONS

L. HABERZETT1, G. WILLIGER1,2, M. D. LEHNERT3, N. NESVADBA5, AND L. DAVIES5,7

1 Department of Physics and Astronomy, University of Louisville, Louisville KY 20492, USA
2 Lab. Fizeau Univ. de Nice, Obs. de Côte d’Azur, 06108 Nice Cedex 2, France
3 IACS, Catholic University of America, Washington, DC 20008, USA
4 GEPI, Observatoire de Paris, UMR 8111 du CNRS, 5 Place Jules Janssen, 92195 Meudon, France
5 Institut d’Astrophysique Spatiale, CNRS, Université Paris-Sud, Bat. 120-121, 91405 Orsay, France
6 Department of Physics, H H Wills Physics Laboratory, University of Bristol, Tyndall Avenue, Bristol BS8 1TL, UK
7 Institute of Cosmology and Gravitation, University of Portsmouth, Dennis Sciama Building, Burnaby Road, Portsmouth, PO1 3FX, UK

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ABSTRACT

We present results of a search for bright Lyman break galaxies (LBGs) at 1.5 ≤ z ≤ 2.5 in the GOODS-S field using an NUV-dropout technique in combination with color selection. We derived a sample of 73 LBG candidates. We compare our selection efficiencies to BM/BX and BzK methods (techniques solely based on ground-based data sets), and find the NUV data to provide greater efficiency for selecting star-forming galaxies. We estimate LBG candidate ages, masses, star formation rates, and extinction from fitting PEGASE synthesis evolution models. We find that about 20% of our LBG candidates are comparable to infrared-luminous LBGs or submillimeter galaxies which are thought to be precursors of massive elliptical galaxies today. Overall, we can show that although BM/BX and BzK methods do identify star-forming galaxies at z ∼ 2, the sample they provide biases against those star-forming galaxies which are more massive and contain sizeable red stellar populations. A true Lyman break criterion at z ∼ 2 is therefore more directly comparable to the populations found at z ∼ 3, which does contain a red fraction.

Key words: galaxies: evolution – galaxies: general – galaxies: high-redshift – galaxies: star formation – infrared: galaxies

Online-only material: color figures

1. INTRODUCTION

Since their discovery in the early 1990s (Steidel & Hamilton 1993), Lyman break galaxies (LBGs) have been used very successfully to study galaxy evolution processes in the high-redshift universe. Using the dropout technique, multi-wavelength surveys have built up large samples of LBGs at redshifts between z ∼ 3–8, where the Lyman break is accessible with solely ground-based data sets (e.g., Steidel & Hamilton 1993; Steidel et al. 1995, 1999, 2003; Lehnert & Bremer 2003; Bouwens et al. 2004). The studies have shown that at z ∼ 4, a significant fraction of the ionizing UV flux is emitted by low-luminosity LBGs (e.g., Lehnert & Bremer 2003; Sawicki & Thompson 2006; Bouwens et al. 2007; Lehnert et al. 2010). Analysis of the stellar populations showed that the population of LBGs at z ∼ 5 consists of significantly less massive and younger galaxies than comparable samples at z ∼ 3 (e.g., Verma et al. 2007; Yabe et al. 2009). Verma et al. suggested that these LBGs are experiencing their first significant buildup of stellar mass (see also Stark et al. 2009). At z ∼ 3, the LBG population consists of more massive galaxies that have formed stars over longer periods (e.g., Shapley et al. 2001; Reddy et al. 2008). A considerable fraction of the z ∼ 3 LBGs (~15%) consists of massive M* > 1011 M⊙ IR-luminous galaxies (Rigopoulou et al. 2006; Magdis et al. 2010); these infrared-luminous Lyman break galaxies (ILLBGs) are considered one possible class of progenitors of today’s massive elliptical galaxies.

Less is known about the LBGs at z ≤ 2.5. At this redshift, the Lyman break occurs in the UV, which can only be observed from space. First studies using deep images observed by the GALEX satellite obtained samples of LBGs at z ∼ 1 using FUV dropouts (Burgarella et al. 2006, 2007; Haberzettl et al. 2009). The majority of LBGs (~75%) at this redshift are disk-dominated, while the rest consist of interacting/merging galaxies (Burgarella et al. 2006).

At z ∼ 2, a number of groups have worked around UV restrictions by using selection techniques which solely rely on ground-based data sets as a proxy method for identifying star-forming galaxies. The BM/BX method (Adelberger et al. 2004; Steidel et al. 2004) is based on U*GR color selection. The color cuts were determined from a sample of spectroscopically verified 1.9 < z < 2.7 star-forming galaxies, which were fitted with dust-reddened spectral energy distributions (SEDs). The resulting best fits were redshifted to z = 1.5, 2.0, 2.5 and used to calculate characteristic colors; for more details see Adelberger et al. (2004).

A second ground-based color method is the BzK selection (Daddi et al. 2004a). The choice of filters covers the flat UV part of the spectra and flanks the Balmer break at rest-frame 4000 Å. This method is sensitive to selecting and distinguishing between star-forming and passively evolving galaxies at z ∼ 1.4. Using the K20 data from the GOODS fields, Daddi et al. identified 25 star-forming and seven old galaxies and reported a high selection efficiency with only 13% contamination by interlopers.

Follow-up studies showed that the optically (BX) selected star-forming galaxies at z ∼ 2 have typical stellar masses on the order of 3 × 10^10 M⊙ and typical star formation rates (SFRs) of ~50 M⊙ yr^{-1} (e.g., Reddy & Steidel 2004; Shapley et al. 2005). Space densities are ~3 × 10^{-3} Mpc^{-3} with a correlation length of r0 = 4.2 ± 0.4 h^{-1} Mpc (Reddy et al. 2005; Adelberger et al. 2005), indicating that typical star-forming galaxies at z ∼ 2 are hosted by ~2 × 10^{12} M⊙ dark matter halos.

Studies of the optical–NIR-selected star-forming galaxies by Daddi et al. (2005) show that a typical BzK galaxy
at $z \sim 2$ is likely to be an ultraluminous infrared galaxy (ULIRG) with $L_{IR} \sim (1-2) \times 10^{12} L_{\odot}$ and star formation rates SFR $\sim 200-300 M_{\odot}$ yr$^{-1}$. The space density of these galaxies is $\sim (1-2) \times 10^{-4}$ Mpc$^{-3}$, which is 2–3 times higher than at $z \sim 0.1$ and 1 (e.g., Sanders et al. 2003; Le Floc’h et al. 2005) and makes them relatively common objects at $z \sim 2$. Their ULIRG nature is also supported by morphological studies using *Hubble Space Telescope* (HST) imaging (Daddi et al. 2004b), indicating that many of the BCzK-selected galaxies show hints of merger events driving strong star formation events.

Dynamical studies of star-forming galaxies at $z \sim 2$ (Forster Schreiber et al. 2009), together with the results from Burgarella et al. (2006), indicate that between redshifts of $z \sim 2$ and $z \sim 1$ is when disk galaxies with significant masses start to contribute to the comoving density of galaxies. It is also the phase when the star formation intensity reaches its peak (Hopkins 2004, and references therein).

From these solely ground-based selection techniques and the development of new instruments like the IFU SINFONI at the Very Large Telescope (VLT) and OSIRIS at Keck, we have learned much about star formation at the critical epoch $z \sim 2$. However, since the selection processes are different to the techniques used for true LBGs at $z \gtrsim 3$, comparisons between the samples are not straightforward. A consistent selection method using the Lyman break, independent of intrinsic galaxy properties, should be used to select consistent samples of star-forming galaxies at $z \sim 2$. Observations require the space-based facilities like *GALEX* or the UV channels of the newly installed WFC3 on board *HST*. First studies include Hathi et al. (2010), Oesch et al. (2010), and Ly et al. (2009, 2011). The latter analyzed a very deep ($\sim 140$ ks) *GALEX* NUV image of the Subaru Deep Field (Kashikawa et al. 2004) and other filters to select true LBGs at redshifts $1.6 < z < 2.7$ and compiled a sample of $\sim 8000$ LBG candidates down to $V = 25.3$ with NUV $\approx 27$, including 24 spectroscopically confirmed at $1.5 < z < 2.7$. For $z \sim 2$ LBGs, they reported a factor $\sim 1.8$ higher summed luminosity density compared to $z \sim 2$ BX and $z \sim 3$ LBGs, and an increase in the luminosity density by a factor of 3–6 between $z \sim 5$ and $z \sim 2$.

Hathi et al. examined *HST*+ WFC3 images (F225W, F275W, and F336W) of a 50 arcmin$^2$ field of the GOODS-S field as part of an extended multi-color survey. The group used $U_{225}$-$U_{275}$-, and $U_{336}$-dropsouts down to $AB = 26.5$ combined with color criteria to select 473 LBG candidates at $z \sim 1.7, 2.1$, and 2.7, respectively. The fitted Schechter function parameters agree well with predictions from other observations with respect to redshift.

These two studies demonstrate the feasibility of selecting samples of true LBGs at $z \sim 2$ consistent with higher redshift $z \gtrsim 3$ LBG samples. Although they are a first step toward better understanding this crucial population of star-forming galaxies at an epoch formally known as the “redshift desert,” currently little is known about their properties. The studies either lack data coverage especially in the NIR and mid-IR (Ly et al. 2009) or field of view available (Hathi et al. 2010).

In this paper, we present first results from a dropout+color selection of a sample of true $z \sim 2$ LBGs based on deep *GALEX* observations of the GOODS-S. Our specific purpose is to target a rarer, brighter sample of LBGs than found in the small, deep survey of Hathi et al. (2010). In addition, it complements the wider study of Ly et al. (2009) because we use a wider range of filters and target a different field to minimize the effects of cosmic variance. We will show that we can obtain a sample of bright $z \sim 2$ LBGs similar to the higher redshift population observed at $z \gtrsim 3$. Here we report first results of estimates of ages, stellar masses, SFRs, and extinction for our purely UV-selected $z \sim 2$ LBG sample. Using the deep *GALEX* UV data available for the CDF-S, we were able to utilize the complete size of the GOODS-S field which offers a wide range of data from the UV to mid-IR and also tripled the Hathi et al. sample size.

The paper is organized as follows: Section 2 summarizes the data used, Section 3 describes our search and defines the selection criteria, and Sections 4, 5, and 6 present photometric redshifts, SED modeling, and the results, respectively. Our summary and conclusions are presented in Section 7. Throughout the paper we use a cosmology with $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_k = 0.7$. All distances quoted are comoving.

## 2. DATA

We base our study on GOODS and supporting surveys, which offer a wide variety of ground- and space-based imaging and spectroscopic data sets, all centered on the CDF-S and HDF-N. We concentrated our studies on the CDF-S, since this field offers the best data coverage. See Table 1 for a complete listing.

### 2.1. GALEX Data

We used very deep *GALEX* FUV and NUV imagery, which is part of the *GALEX* Deep Imaging Survey (DIS). The data set consists of a 87 ks FUV and a 89 ks NUV exposure centered on the CDF-S (Martin et al. 2005) covering a $\sim 1$ deg$^2$ field of view. Without deconvolution, the data (FUV and NUV) provide a $3\sigma$ detection limit of $m_{AB} = 24.5$ (MAG_ISO from SExtractor). Confusion noise in such deep images, with the large *GALEX* point spread function (PSF) ($\sim 5\prime\prime 4$), contributes to decreasing the detection sensitivity of the data. However, since we were interested in the detection of LBGs at $z \sim 2$, where the Lyman break is shifted in the NUV band, it is the non-detections and the detection limits that are important. Therefore, our results are not seriously affected by confusion or overlapping sources, and consequently we did not deconvolve the NUV images. We adopted an effective detection limit where the completeness reaches $\sim 70\%–75\%$ at $m_{AB} (\text{FUV}) \sim 26.2$ and $m_{AB} (\text{NUV}) \sim 26.7$ within a $5\prime\prime$ aperture (Figure 1). We calculated the completeness using simulated images created with *skymaker v3.3.3* and verifying detection probability using *SExtractor*. Figure 1 has been generated using a magnitude bin size of 0.125. The process was repeated 100 times, with 50,000 stars deg$^{-2}$ between 18 and 28 mag per iteration. The errors for the completeness are represented by the standard deviations for the single bins. The smooth decline in completeness, starting around $\sim 23$ mag, correlates with the number density of the simulated objects and can be interpreted as a result of confusion due to the large PSF of the *GALEX* data. The steep decrease at faint magnitudes (marked by the big crosses in Figure 1) indicates where the sample starts to become rapidly incomplete. We chose a threshold of $\sim 70\%–75\%$ because it is where the steepest decline sets in and thus becomes very sensitive to photometric uncertainties, i.e., the detection or non-detection of sources becomes sensitive to even small photometric errors.

To avoid false detections or non-detections (for example, due to objects being merged with bright and/or extended neighbors) we visually inspected each candidate. The relatively small number of objects made this inspection straightforward, and $\sim 10\%$ of the objects had multiple identifications which could
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Figure 1. Results of the completeness calculations for the CDF-S GALEX data. Left: FUV completeness distribution showing a level of 70%–75% at a limit of ∼26.2 AB. Right: NUV completeness distribution indicating a level of 70%–75% for ∼26.7 AB.

Table 1
Summary of Data Used

| Survey   | Filter | Telescope          | Tot. Exp. Time (s) | FWHM (arcsec) | $m_{\text{lim}}$ (ABmag) | Comment                |
|----------|--------|--------------------|--------------------|---------------|--------------------------|------------------------|
| GALEX DIS | FUV    | GALEX              | 87042              | 4.5           | 27.0$^a$                 | Martin et al. (2005)   |
| GALEX DIS | NUV    | GALEX              | 89199              | 5.6           | 26.5$^a$                 | Martin et al. (2005)   |
| GaBoDS   | $U$    | ESO/MPG 2.2 m+WFI  | 78891              | 1.01          | 26.3$^b$                 | Hildebrandt et al. (2005) |
|          | $B$    |                    | 69431              | 0.98          | 27.2$^b$                 | Hildebrandt et al. (2005) |
|          | $V$    |                    | 104603             | 0.92          | 26.8$^b$                 | Hildebrandt et al. (2005) |
|          | $R$    |                    | 87653              | 0.79          | 26.8$^b$                 | Hildebrandt et al. (2005) |
|          | $I$    |                    | 34575              | 0.93          | 25.0$^b$                 | Hildebrandt et al. (2005) |
| GOODS/GEMS | F850LP | HST+ACS            | 18232              | 0.03          | 26.0                     | Giavalisco et al. (2004b) |
|          |        |                    |                    |               |                          | Rix et al. (2004)       |
| GOODS     | $J$    | VLT+ISAAC          | (15500)            | (0.44)        | <25.5$^c$                | Giavalisco et al. (2004) |
|          | $K_s$  | Data release v1.0  | (20200)            | (0.47)        | <25.2$^c$                | Giavalisco et al. (2004) |
| [3.6]    | Spitzer+IRAC | 82800, 16560$^d$ | 3.6              | ~24.0         | M. Dickinson et al. 2012, in preparation |
| [4.5]    | Spitzer+IRAC | 82800, 16560$^d$ | 3.6              | ~23.0         | M. Dickinson et al. 2012, in preparation |
| [5.8]    | Spitzer+IRAC | 82800, 16560$^d$ | 3.6              | ~23.0         | M. Dickinson et al. 2012, in preparation |
| [8.0]    | Spitzer+IRAC | 82800, 16560$^d$ | 3.6              | ~23.2         | M. Dickinson et al. 2012, in preparation |
| [24.0]   | Spitzer+MIPS | 82800             | 3.6              | ~20.5         | M. Dickinson et al. 2012, in preparation |
| MOS      | VLT+VIMOS | (14200)           | $U_{\text{CTIO}} \sim 26$ |              | Popesso et al. (2009)    |
| MOS      | VLT+FORS2 | (39000)           | $z_{\text{ESO}} < 26$ |              | Vanzella et al. (2008)   |

Notes. Unless otherwise noted, $m_{\text{lim}}$ is a 3σ detection limit.

$^a$ 1.5σ detection limit used within SExtractor search.

$^b$ 5σ detection limit within a 2″ aperture.

$^c$ 10σ detection limit within a 1″ aperture.

$^d$ Total exposure time for the central overlap region.

implies mergers or clumpy extinction but probably not separate but overlapping sources.

2.2. Optical and NIR Data

We used deep public images from the GaBods survey for the object search and color selection of LBG candidates (Hildebrandt et al. 2005). The data set offers 0.25 deg² $UBVRI$ pointings centered on the CDF-S, and was observed using the ESO/MPG 2.2 m telescope with the Wide Field Imager (WFI). The images reach 5σ detection limits in $UBVRI$ for a 2″ aperture of 26.3, 27.2, 26.8, and 26.8. For more details see Table 1.

Deep NIR data are available as part of the GOODS survey observed using ISAAC at the ESO VLT (Giavalisco et al. 2004b). We used data release v1.0 covering a 10′ × 16′ area observed in the J and $K_s$ filters and reaching 3σ detection limits of <25.5 and <25.1, respectively. The images yield an average resolution of (0.44) arcsec in J and (0.47) arcsec in $K_s$.

Besides the ground-based broadband imaging, we also used high-resolution space-based imaging covered with Advanced Camera for Surveys (ACS) on the HST, in particular data from...
GOODS (Giavalisco et al. 2004a) as well as GEMS (Rix et al. 2004), observed in the Sloan z band. The data offer a pixel size of 0.03 or ~250 pc at $z \sim 2$, and provide us with basic morphological information for $1.5 \leq z \leq 2.5$ LBG candidates.

2.3. Spitzer Data

Additional photometric information in the mid-IR was provided by deep Spitzer images observed in the 3.6, 4.5, 5.8, 8.0, and 24 μm bands. The data are part of the GOODS survey and were observed as a Spitzer Legacy program in 2004; we used the data version v0.3 (M. Dickinson et al. 2012, preparation). The images cover 10′ × 16′. Due to the observing strategy for the IRAC bands (3.6–8.0 μm), which are comprised of two exposures taken 6 months apart and rotated 180° against each other, the central 1/3 ultra-deep parts of the final images were exposed twice as long as the outer super-deep regions (Table 1). The MIPS data were only observed during the epoch 1 observing campaign and correspond to the super-deep IRAC images. The Spitzer data cover the rest-frame NIR for the selected $z \sim 2$ LBGs, and probe the older low-mass part of the stellar populations, thus better constraining the SED fits.

2.4. Spectroscopic Data

Redshift information is available for parts of our sample from the GOODS-ESO observations with VLT+VIMOS (Popesso et al. 2009). We used redshifts from the low-resolution VIMOS LR-Blue grism data, which have a spectral resolution of ~28 Å, with a 5.7 Å pixel$^{-1}$ dispersion. The spectra cover 3500–6900 Å (1167–2300 Å at $z = 2$). A second set of redshifts used in our study was also available via GOODS, and was obtained with the VLT+FORS2 (Vanzella et al. 2005, 2006, 2008). The observations were taken using the 300I grism without an order-separating filter, resulting in a 3.2 Å pixel$^{-1}$ dispersion and a 9 Å resolution at 8000 Å, spanning 6000–10000 Å. For this study we could use a total of 1075 redshifts in the field, covering $0 \leq z \leq 5$.

2.5. Photometry

In the following, unless stated otherwise, we will solely concentrate on the analysis of objects found in the GOODS-S, the inner part of the CDF-S which is covered extensively in all 13 filter bands. Since the smallest total area coverage (~140 arcmin$^2$) is offered by the NIR data observed by ISAAC on the ESO VLT, we used it to determine the area over which we selected our final sample.

Throughout this paper we employ both aperture and total magnitudes. We used the aperture photometry for photometric redshift estimations and SED fitting. To perform aperture photometry we applied the apert task from NASA’s IDL Astronomy User’s Library. We measured the fluxes using apertures with equal radii of 2′′ in the optical and the NIR filter bands based on double the FWHM of 1′ in the $U$ band which functions as our detection filter. However, since the GALEX and Spitzer data offer much lower spatial resolution, we modified the aperture sizes accordingly (6′′ for GALEX FUV and NUV bands and 4′′ for the IRAC bands). We did not determine aperture magnitudes for the Spitzer 24 μm MIPS images.

To account for aperture losses, we derived aperture corrections in every filter band using a set of about 100 stars found in the GOODS-S field (Groenewegen et al. 2002). The aperture corrections and their uncertainties range between 0.98±0.78 for the GALEX FUV and 0.14 ± 0.17 for the ISAAC $K_s$ (Table 2), and were calculated from the growth curves using the mean aperture magnitudes and standard deviations of the stellar sample. The total errors for the aperture magnitudes were determined by adding the uncertainties of the magnitude zero points and aperture corrections to the errors determined by $aper$ in quadrature. For the Spitzer IRAC bands we used the following magnitude zero-point errors: $Δm_{1.6} = 0.05$ mag, $Δm_{4.5} = 0.05$ mag, $Δm_{5.8} = 0.04$ mag, $Δm_{8.0} = 0.06$ mag, which were calculated from the flux uncertainties of the flux zero points given in the Spitzer manual.

We adopted total magnitudes from the SExtractor MAG_ISO-magnitudes. These total magnitudes were used for the color selection of the LBG sample (see Section 3) and the IR color–magnitude diagrams in Section 6.2.

### Table 2

| Filter | Radius (″) | $m_{aper}$ (ABmag) | $Δm_{aper}$ (ABmag) |
|--------|------------|---------------------|---------------------|
| FUV    | 3.0        | 0.98                | 0.78                |
| NUV    | 3.0        | 0.81                | 0.48                |
| U      | 1.0        | 0.35                | 0.17                |
| B      | 1.0        | 0.28                | 0.07                |
| V      | 1.0        | 0.27                | 0.07                |
| R      | 1.0        | 0.23                | 0.08                |
| I      | 1.0        | 0.31                | 0.10                |
| J      | 1.0        | 0.14                | 0.11                |
| $K_s$  | 1.0        | 0.14                | 0.17                |
| [3.6]  | 2.0        | 0.34                | 0.10                |
| [4.5]  | 2.0        | 0.21                | 0.08                |
| [5.8]  | 2.0        | 0.17                | 0.06                |
| [8.0]  | 2.0        | 0.31                | 0.17                |

3. SEARCH AND COLOR SELECTION

To select LBG candidates in the redshift range $1.5 \leq z \leq 2.5$, we first detected possible candidates performing SExtractor searches in every single filter band. Specifically, we did not extract sources from one image based on the detection of an object in another image. Rather, we detected objects in every filter band independently, and then measured total magnitudes for them. The resulting object catalogs were then cross-correlated against each other, creating a master catalog including all imaging results. For the correlation, we applied matching radii according to the spatial resolution of the images used (Table 1, Column 5). As a final step, we matched the imaging master catalog with the two spectroscopic catalogs from GOODS (VIMOS and FORS spectroscopy).

To identify LBG candidates at $1.5 \leq z \leq 2.5$, we employed two different approaches. We limited the size of the field searched to the area of the sky covered by the ISAAC NIR observations. Since this data set covers the smallest area, this step guaranteed to restrict our sample only to candidates observed in all 13 filter bands. Over this field we selected all $U$-band sources brighter than 25.3 (AB magnitudes) with no detection in the FUV and NUV bands (NUV dropouts, i.e., NUV $\lesssim 26.7$ in a 5″ aperture), and compared their locations in a $U−B$ versus $B−R$ color–color diagram to those of model galaxies at $1.5 \leq z \leq 2.5$ (Figure 2). The $U$-band selection limit allowed us to detect objects with a Lyman break (NUV-U) of at least 1.4 mag.

We calculated model galaxy colors using template SEDs from Fioc & Rocca-Volmerange (1997; PEGASE) and Bruzual &
Figure 2. Lower panels: selection regions defined by a series of model colors of star-forming galaxies in the two-color plane, with models indicated in the key. Blue dash-dotted quadrilaterals: color selection criteria used for LBG candidates at $1.5 \leq z \leq 2.5$ (the largest selection regions, which include all other selection regions). Blue solid quadrilaterals, left panels: BX color criteria (optically selected star-forming galaxies for $2.0 < z < 2.6$). Blue dashed strip below/blueward of BX region, left panels: BM color criteria (optically selected star-forming galaxies for $1.25 < z < 2.0$), BM/BX from Steidel et al. (2004). We select objects for two groups of LBG candidates. (a) Cyan diamonds, upper left panel: NUV dropouts with colors complying with the largest quadrilateral selection box in the $B-R$ vs. $U-B$ diagram. (b) Red diamonds, upper two panels: objects at $1.5 \leq z \leq 2.0$ detected in the NUV band and possessing colors complying with the selection boxes in both color–color diagrams. Blue diamonds: a subsample of 25 NUV dropouts with spectroscopically confirmed redshifts at $1.5 \leq z \leq 2.5$. Black dots: complete $U$-band detected sample in the GOODS-S field.

(A color version of this figure is available in the online journal.)

Table 3
Template SEDs Used for Deriving Color Selection Criteria (Figure 2)

| Model                  | Star Formation Law | Age (Gyr) |
|------------------------|--------------------|-----------|
| Irr Bruzual & Charlot (2003) | Constant           | 2–3.7     |
| PEGASE                 | Burst              | 0.5       |
|                        | Exponential decrease | 0.5    |
|                        | Exponential decrease | 1.0   |

Charlot (2003), and employed the photo-z algorithm HYPERZ (Bolzonella et al. 2000) to derive the model color tracks (Table 3) for a variety of star formation laws, ages, and dust properties (Figure 2, bottom row). The template SEDs were extinction-adjusted via HYPERZ using the reddening law of Calzetti et al. (2000) and $A_V$ ranging between 0 and 1.2. We further accounted for absorption by the Lyα forest on the SEDs using the method from Madau (1995) within HYPERZ.

The location of the model galaxies in the $U-B$ versus $B-R$ diagram defined the color selection criteria (largest blue dashed quadrilaterals in Figure 2) for $z \sim 1.5$–2.5 galaxies which, with the NUV Lyman break, we used to select our LBG candidates (Figure 2, top row). The color cuts are

$$NUV > 26.70$$

$$B - R \geq -0.53$$

$$U - B \geq 0.70 (B - R) - 0.04$$

$$B - R \leq 0.31 (U - B) + 0.56$$

$$U - B \leq (B - R) + 1.22.$$
Lyman break falls within the NUV band (2280 Å < λ < 2736 Å). Those color cuts are (Figure 2, left panels)

\[
\begin{align*}
FUV & > 26.2 \\
NUV - U & \geq 1.50 \\
U - B & \geq -0.41 \\
U - B & \leq 2.59.
\end{align*}
\]

The NUV-selected LBG candidates had to meet both sets of color selection criteria, and be detected in the NUV but not in the FUV. The \(U - B\) limits in the NUV – \(U\) versus \(U - B\) diagram were the same as in the \(U - B\) versus \(B - R\) diagram, while the NUV – \(U\) \(\geq 1.5\) limit represents the blue end of the model SED tracks.

Finally, we cleaned our selected sample for stellar contamination by comparing it with a stellar catalog (Groenewegen et al. 2002), which was created using a magnitude-limited SED model SED tracks.

\[
53 \text{ NUV-dropout LBG candidates (see Figure 3 for two example images in the available filter bands) and 20 NUV-selected LBG candidates down to } U < 25.3.
\]

4. PHOTOOMETRIC REDSHIFTS

Using our 13-band photometry from UV to IR (GALEX FUV to Spitzer 8 μm, but excluding the ACS \(z\) band), we estimated photometric redshifts with HYPERZ v1.3 (Bolzonella et al. 2000). The redshift determination was done by cross-correlating a set of template spectra to the colors of our sample galaxies. In the current version of HYPERZ, we used a set of five template spectra from Bruzual & Charlot (2003), consisting of an elliptical, Sc, Sd, Irr, and starburst galaxy. In cases where the objects were not detected in a filter band, except for the GALEX FUV and NUV bands, we omitted the non-detection for the redshift determination. To account for the Lyman break, the flux levels in the GALEX FUV and NUV bands were set to zero during the template correlation. HYPERZ can account for the effect of the Ly\(\alpha/\Ly\beta\) forest, therefore we applied the corresponding Ly\(\alpha\) forest opacity estimates of Madau (1995). We accounted for internal reddening of the LBG candidates by employing the reddening law of Calzetti et al. (2000), with \(A_V\) set to range between 0 and 1.2 mag in steps of 0.2. The resulting redshift distributions for galaxy samples selected with the BM/BX, BzK, and our dropout technique are shown in Figure 4. The peak at low redshift } \ z < 2 \text{ in the dropout and NUV-selected sample (left panel) is mainly due to residual stellar contamination. Five stars were identified when checking the } HST \text{ images by eye. One of the low-redshift galaxies, selected with the NUV selection method, clearly shows flux in the FUV filter band. The flux is weak and merged with emission from a nearby bright star,
leading to a false non-detection. Both the star and the galaxy were removed from the sample and not considered for further analysis. The second low-redshift galaxy, selected with the NUV-dropout method, does not show obvious emission in the UV filter bands. We therefore keep this object in our sample at this stage. Our subsequent analysis will use redshift limits to restrict the sample further, minimizing the effects on the results by foreground or background objects.

While our NUV-dropout selection and the BM/BX method allowed for a relatively clean selection of z ~ 2 star-forming galaxies, the contamination with low-redshift interlopers is much higher for the BzK selection method.

We calculated photometric redshift uncertainties $dz_{\text{offset}} = (z_{\text{phot}} - z_{\text{spec}})/(1 + z_{\text{spec}})$ (Figure 5, right panel). Overall, the rms is $\delta z_{\text{rms}} = 0.24$, with an averaged offset of $\langle dz_{\text{offset}} \rangle = 0.13$. The fraction of catastrophic outliers ($\delta z_{\text{rms}} > 3\sigma$) is 14%. The accuracy of the photometric redshift estimation increases with the use of our LBG selection method: for our LBG candidate sample, the rms is $\delta z_{\text{rms}} = 0.198$, with an average of $\langle dz_{\text{offset}} \rangle = 0.095$, indicating no significant systemic offsets. The fraction of catastrophic outliers decreased to ~5% (1/20). We therefore conclude that the photometric redshift determination enables us to estimate unbiased photometric redshifts for our LBG sample.

Our library consisted of several thousand PEGASE spectra including star formation histories with constant and exponentially decreasing SFRs. The decay times $\tau$ for the exponentially decreasing SFRs range from $\tau = 10$ Myr (burst-like scenarios) to $\tau = 5000$ Myr (close to constant star formation).

We modeled the SEDs using a Kroupa et al. (1993) initial mass function, including consistent chemical evolution and following a closed box approach excluding gas infall and outflow. Although it is likely that high-redshift star-forming galaxies have outflows (e.g., Steidel et al. 2010), we decided not to consider outflows in the PEGASE SEDs. Again, this allows for a better comparison with previously published results based on the Bruzual & Charlot models.

The model fits and the conversion into physical parameters (mass, SFR, $E(B-V)$) were done using an IDL-based chi-square minimization routine. Our routine applies the Calzetti et al. (2000) extinction law to the PEGASE models for dust correction. We chose the Calzetti et al. law since it has been used by many other studies of high-redshift galaxies (e.g., Shapley et al. 2001, 2005; Yabe et al. 2009). We applied extinction corrections to the PEGASE model SEDs ranging between $A_V = 0–5$ mag in steps of 0.1 mag. The extinction-corrected PEGASE models were then redshifted and fitted following the chi-square minimization approach described by Gwyn & Hartwick (2005). The normalization of the measured SEDs was derived including only the observed frame optical (U BV R) filter bands.

When possible, we employed spectroscopic redshifts, and photometric redshifts otherwise.

From the model fits we estimated ages, stellar masses, SFRs, and dust extinction $E(B-V)$ for LBG candidates. Our results only allow for best-fitting SEDs which were younger than the age of the universe (maximum age approach). We estimated uncertainties for the calculated parameters as the standard deviation of the expectation value of each parameter (see Noll et al. 2009 for more details). We restrict the final sample of LBG candidates to galaxies with photometric and spectroscopic redshifts $1.0 \leq z \leq 2.5$, which includes 61 objects.

The SED fitting resulted in a median of the reduced $\chi^2$ values for the complete sample, $\chi^2 = 1.83 \pm 1.70$. Acceptable fits with a probability of 0.1% (1%) have $\chi^2 \leq 3.25 (2.5)$ and make
up about 70% (56%) of the sample. Larger reduced $\chi^2$ values appear to result from two main sources.

1. Small photometric errors, especially in the NIR and mid-IR filter bands, indicating that we are underestimating the photometric uncertainties in these bands.

2. Uncertainties in the photometric redshift estimation. We find that reduced $\chi^2$-values for objects with spectroscopic redshifts ($\sim 34\%$) are smaller than for objects with only photometric redshifts available. The median-reduced $\chi^2$ for the objects with spectroscopic redshifts is $\chi^2 = 1.18 \pm 1.53$, with about 83% having $\chi^2 \leq 3.25$, while the median-reduced $\chi^2$ for the objects with only photometric redshifts is $\chi^2 = 2.63 \pm 1.70$. This indicates that uncertainties in the photometric redshift estimation resulted in higher uncertainties in the SED fits. Since even small redshift uncertainties can have large implications for the fit result when including the NUV filter (especially for the lower redshift LBGs $z \sim 1.5$), we decided to exclude the NUV and FUV photometry from the SED fits.

The majority of best-fitting models are those with either constant SFRs (11%) or long decay times ($\tau = 150$–$500$ Myr) and SFRs versus their $\chi^2$-values and their errors. However, the highest masses ($>10^{10} M_\odot$) seem to be best constrained, showing the smallest uncertainties. In contrast, the uncertainties for the ages are large, with a median value of 0.9 dex. Older galaxies in the sample ($>500$ Myr) are found to have relatively well-constraint ages with a median error of $\sim 0.4$ dex. Unlike the stellar mass and the SFRs, the ages show an increase in uncertainties with increasing $\chi^2$. Therefore, most of the uncertainties in the best-fitting models lie in the age estimates.

Examples of successful SED fits are shown in Figure 6. The right panel shows an SED for which only photometric redshifts were available, while the left panel shows an example fit for which the spectroscopic redshifts could be used.

6. RESULTS

6.1. Dropout Selection

From the GOODS-S spectroscopic data (Vanzella et al. 2008; Popesso et al. 2009), we were able to obtain spectroscopic redshifts for 25 (20 dropout and 5 NUV-selected) of our 67 total LBG candidates. About 80% of the dropout-selected (16/20) and only 20% (1/5) of the NUV-selected LBG candidates were found to have redshifts in our target range of $1.5 \leq z \leq 2.5$. However, an additional $\sim 15\%$ (3/20) of the NUV dropouts and 60% (3/5) of the NUV-selected objects have $1.0 < z < 1.5$. Including this poorly explored redshift range, inaccessible from the ground for true dropout identifications, increased the selection efficiency from $\sim 80\%$ to 95% for the dropout-selected and 20% to 80% for the NUV-selected LBG candidates.

Comparison with BM/BX. In the last few years, several selection methods like the BM/BX (Steidel et al. 2004; Adelberger et al. 2004) and BzK methods (Daddi et al. 2004a, 2004b) have been employed, which solely rely on ground-based photometry to create samples of star-forming galaxies at $z \sim 2$. We compared the selection efficiency of these methods here to our dropout selection which directly probe their Lyman break spectral regions, and thus are more directly analogous to the LBG samples at $z > 3$. To avoid effects due to selecting fainter objects especially with the BM/BX method, we applied the same brightness limits ($U \leq 25.32$ AB) as for the dropout selection. Figure 2 shows our Lyman break+color criteria (large dot-dashed quadrilaterals, left panels) compared to the BM/BX method (smaller solid/dashed blue quadrilaterals, respectively). The overlap is relatively small and consists mainly of model galaxies with relatively complex star formation histories (e.g., exponentially decreasing SFRs). The allowed LBG parameter space increases when including more evolved and/or dust-reddened cases—because the dropout method does not depend on (optical) colors redward of the rest-frame Lyman limit. In summary, only 2/3 of the NUV-dropout-selected sample of LBG candidates (34 of 53) are detected with the BM/BX criteria, and only about 60% of the BM/BX-selected galaxies (26 of 45) would have been selected by our color plus NUV-dropout criteria.

Comparison with BzK. Only nine LBG candidates ($\sim 20\%$ of the NUV-dropout-selected LBG candidates) satisfy the BzK “$B-z$ versus $z-K_s$” color requirement. Only $\sim 25\%$ of the BzK-selected galaxies (11 of 48) were found to be NUV dropouts and about $\sim 80\%$ of the BzK NUV dropout candidates (9 of 11) were located within our color selection region in the $U-B$ versus $B-R$ diagram (Figure 2).
These results show that a true Lyman break selection targets a different population of galaxies, perhaps more evolved and/or reddened than the BM/BX-selected galaxy population and more similar to the $BzK$ selection. Our dropout selection targets mainly bright star-forming galaxies due to limitations in the sensitivity, especially in the $K$ band. However, compared to the $BzK$ selection, the dropout technique reduces the contamination due to interlopers and results in a cleaner, more complete sample of $1.5 \leq z \leq 2.5$ LBGs (Figure 7).

6.2. Masses, SFRs, and Extinction

Fitting the PEGASE synthesis evolution models, we find that our UV-bright LBG sample is best represented by ages ranging between $0.004$ and $3$ Gyr (Figure 8), stellar masses between $9 \times 10^8$ and $2 \times 10^{10} M_\odot$, and SFRs up to $270 M_\odot$ yr$^{-1}$ (Figure 9) with a median SFR $= 50 \pm 53 M_\odot$ yr$^{-1}$. The sample is relatively strongly reddened, with a median $A_V = 1.1 \pm 0.5$. The age distribution peaks around $0.1$ Gyr (Figure 8), with a possible second smaller peak around $2$–$3$ Gyr. We see a lack of the very young galaxies $\lesssim 10^7$ Myr found by Shapley et al. (2005), indicating that our color selection compared to the BX-selected star-forming galaxies at $z \sim 2$ of Shapley et al. is more sensitive to evolved galaxies with moderate SFRs. However, when comparing the stellar mass and SFR distribution, we find that the dropout technique is more sensitive to moderate masses with a peak around $10^{10} M_\odot$ and SFRs higher than those at $z \sim 3$ (e.g., Shapley et al. 2001), peaking at relatively high SFRs of about $100 M_\odot$ yr$^{-1}$. Similar to Verma et al. (2007), we find that our $z \sim 2$ LBGs are more massive, older, and have similar SFRs compared to high-redshift LBGs, for example, the $z \sim 5$ LBGs of Yabe et al. (2009).

In general, the properties of our dropout-selected LBGs based on the SED fits are more comparable to LBGs at $z \sim 3$.
Figure 9. Comparison of masses and SFRs between our dropout-selected $z \sim 2$ LBGs (black and blue squares), the $z \sim 2$ BX-selected star-forming galaxies (red filled circles), the $z \sim 3$ LBGs of Shapley et al. (green filled circles), and $z \sim 5$ LBGs of Yabe et al. (2009) (cyan diamonds). For high star formation rate systems, the Lyman-break-selected galaxies have higher masses than the BM/BX sample for a given SFR. The error bars in the upper left corner indicate typical errors for stellar masses, SFRs, and ages.

(A color version of this figure is available in the online journal.)

Figure 10. $[3.6] \text{ vs. } [8.0]$ (left panel) color–magnitude diagram using Spitzer measurements for our LBG candidate sample. Black dots: all galaxies in our sample with either IRAC 3.6 $\mu$m (left panel) or IRAC 8.0 $\mu$m and MIPS 24 $\mu$m (right panel) detections. We compare our measurements to results for $z \sim 3$ ILLBGs reported by Rigopoulou et al. (2006, open diamonds). We also make a similar comparison in the $[8.0] \text{ vs. } [24]$ color–magnitude diagram (right panel). Orange diamonds, left panel: LBGs from our sample which are also detected in the Spitzer 8 $\mu$m but not in the 24 $\mu$m band. Open diamonds without open stars, right panel: LBGs from the $z \sim 3$ LBG sample of Rigopoulou et al. (2006) detected in 8 $\mu$m but not 24 $\mu$m.

(A color version of this figure is available in the online journal.)

(e.g., Shapley et al. 2001) than are BM/BX- and $BzK$-selected galaxies. Our results demonstrate the consistent selection of the dropout technique over a large redshift range, which allows for the compilation of comparable samples to study the evolution of galaxies over cosmic timescales.

6.3. IR-luminous LBGs

A small fraction of our LBG candidate sample has colors in the $R - [3.6]$ versus [3.6] color–magnitude diagram (Figure 10) comparable to ILLBGs and submillimeter galaxies at $z \sim 3$ (e.g., Rigopoulou et al. 2006). The location in the color–magnitude diagrams indicates that our LBG sample consists of about 20% ILLBGs and/or galaxies consistent with submillimeter galaxies. The estimated median stellar mass of the IR-luminous subsample is $7.9 \pm 4.1 \times 10^9 M_\odot$, and is slightly higher than the median stellar mass of the total LBG sample ($5 \pm 4.1 \times 10^9 M_\odot$). With a median SFR of $84 \pm 62 M_\odot \text{ yr}^{-1}$, the IR-luminous subsample consists mainly
of LBGs with high SFRs ($\gtrsim100\,M_\odot\,\text{yr}^{-1}$), while the distribution for the general LBG sample shows a tail of LBGs with lower SFRs ($\lesssim30\,M_\odot\,\text{yr}^{-1}$). The higher median extinction of $A_V = 1.4 \pm 0.8$ for the ILLBGs ($A_V = 1.1 \pm 0.5$ for the complete sample) indicates that light can be subjected to opacities well beyond $\tau = 1$, even in the optical. The implication is that there is still some part of the star formation that could be hidden by dust, resulting in an underestimate of the SFRs. The high dust reddening of the ILLBGs is also supported by the fact that all IR-luminous candidates are found with relatively red colors in the color–color diagrams, not falling in the overlap region between BM/BX and dropouts ($(U-B) = 0.72 \pm 0.21$ and $(B-R) = 0.53 \pm 0.27$ consistent with recent results for a small far-IR detected sample by Burgarella et al. (2011). Although our results indicate substantial reddening due to larger amounts of dust, we have to be careful when drawing conclusions concerning extinction from UV and optical data alone. The age-extinction degeneracy and the lack of FIR data, where the thermal emission of dust defines the spectral properties, makes any interpretation difficult at best. Using the results from the best-fitting SEDs of our sample, we determine a median error for the extinction of $\Delta A_V \lesssim 0.5$. In all cases we find no acceptable fits with $A_V > 2.3$ mag, with the largest extinction corrections being found for the ILLBGs.

We also calculated the total IR luminosity following the approach of Rieke et al. (2009), estimating $L_{\text{TIR}}$ from the 24 $\mu$m flux using a linear approximation. The luminosities are given in $L_\odot$, employing apparent solar magnitudes using Rieke et al. (2008) and Engelke et al. (2010). We thus estimated total IR luminosities for our subsample of ILLBGs of $6 \times 10^{10} - 1 \times 10^{12} L_\odot$, with a median total IR luminosity of $L_{\text{TIR}} = 4 \times 10^{11} L_\odot$. Using the conversion reported by Nordon et al. (2010) this translates into a factor of two lower median SFR of about $40\,M_\odot\,\text{yr}^{-1}$ for the ILLBG sample than derived from the SED model fits.

Compared to LBG samples at higher and lower redshifts with similar mass and UV luminosity ranges, we find that our sample consists of galaxies which have moderately higher extinction. Studies at $z \sim 5$ and $z \sim 3$ estimate median extinctions of $A_V \approx 0.3-0.9$ (e.g., Verma et al. 2007; Yabe et al. 2009) and $A_V = 0.5$ (e.g., Shapley et al. 2001), respectively. At $z \sim 3$ the ILLBG sample of Rigopoulou et al. (2006) shows a median extinction of $A_V \sim 1.0$. Although slightly higher than the general samples of LBGs at this redshift, their reddening is lower than the median extinction of $A_V = 1.4$ found in this study. Extinction values ($A_V = 0.8-1.8$) similar to ours have been estimated for an 8 $\mu$m and 24 $\mu$m detected sample of LBGs by Shim et al. (2007). However, their sample consists mainly of ULIRG-like, massive LBGs with stellar masses of up to $10^{12} M_\odot$ and IR luminosities of $L_{\text{IR}} \gtrsim 10^{12} L_\odot$. Thus our selection, which in general selects $z \sim 2$ LBGs, nevertheless favors selecting galaxies with higher extinction compared to $z \gtrsim 3$ LBGs. This is because we require them to be detected in all bands, including in the IR.

At lower redshifts, studies revealed LBGs with extinction values similar to the ones found at $z \gtrsim 3$. At $z \gtrsim 1$ Nilsson et al. (2011) estimated extinctions of $A_V = 0.5-2$, with a median of 0.8 for a sample of LBGs in the GOODS-S field (Burgarella et al. 2007). Similarly, at $z \sim 0.1-0.2$, Lyman break analogs are found to have a median extinction of $A_V = 0.8$ (Overzier et al. 2011). While overall trends in the extinction with redshift are difficult to determine, it appears that our study stands out in selecting galaxies with moderately higher extinction on average than other samples at lower and higher redshifts.

Compared with other published examples of IR-luminous LBGs, we find that our sample consists of galaxies with moderate masses having a median mass of $\sim 8 \times 10^{10} M_\odot$. This is comparable to the $z \sim 1$ LBGs of Nilsson et al. (2011), which have masses between $1.3 \times 10^{9} M_\odot$ and $3.6 \times 10^{10} M_\odot$. At $z \sim 3$, ILLBGs appear to be more massive. Rigopoulou et al. (2006), for example, found IR-bright LBGs with masses between $4 \times 10^{10} M_\odot$ and $4 \times 10^{11} M_\odot$. Even higher masses of $10^{12} M_\odot$ have been reported for 24 $\mu$m detected LBGs by Shim et al. (2007). With IR luminosities of $L_{\text{IR}} \gtrsim 10^{12} L_\odot$, these galaxies are massive, dusty ULIRGs. The very high mass LBGs are relatively rare and might have been missed by us due to our relatively small search volume. Also, the lack of very massive LBGs in our sample might have been due to limiting our selection to UV-bright objects, requiring detections from $U$ to IRAC 4.5 $\mu$m (observed frame). Both of these criteria (UV and IR-luminous) favor the selection of objects with patchy extinction. Such galaxies possess strong, obscured starbursts. However, the extinction is patchy such that light from a UV-emitting stellar population, or less obscured star formation, can be observed. This can be seen in Figure 11, where some of the galaxies have a complex morphology. The ILLBGs represent the more massive, dusty, heavily star-forming tail of the LBG population in our study, but are less massive than their high SFR, dusty counterparts at higher redshifts.

These galaxies might also resemble an interesting part of the high-redshift sources contributing to cosmic IR background (CIB) light. At $z \sim 2$ about 30%-40% of the CIB results from luminous infrared galaxies (LIRGs; Berta et al. 2010), which are comparable to our ILLBGs. In addition, FIR observations show that at $\lambda \gtrsim 350$ $\mu$m more than half of the contribution to the CIB comes from sources at redshifts $z \gtrsim 1.2$ (Devlin et al. 2009). Thus, a significant fraction of the SFR at this epoch might be provided by dusty IR-bright galaxies.

### 6.4. Morphology

From an inspection of the high-resolution HST+ACS images by eye, we conclude that the majority of the LBG sample consists of galaxies showing indications of disk-like structure, while the rest can be considered compact objects (examples shown in Figure 11). Also, the majority of the sample has at least one close (<3′) neighbor or shows disturbed disk structures, such that they may be considered merger candidates. For the ILLBG subsample, we find that about 80% show indication of a disk structure and 20% are found to be compact objects. About 50% of the ILLBGs can be considered merger candidates. Although these results have to be taken carefully, since we did not apply detailed morphological analysis and a judgment by eye is very subjective, they seem to be in agreement with results found by Burgarella et al. (2006) for the $z \sim 1$ LBGs which consist of about 75% disk-dominated galaxies and $z \sim 1$ LIRGs (e.g., Melbourne et al. 2005; Bell et al. 2005; Hammer et al. 2007). A more detailed analysis of the morphology will be presented in a later paper (L. Haberzettl et al. 2012, in preparation).

### 7. SUMMARY AND CONCLUSION

We present results of a search for LBGs at $1.5 \leq z \leq 2.5$, an epoch once called the redshift desert. Over the last few years, studies employing the BM/BX (Steidel et al. 2004; Adelberger...
Our selection method resulted in a success rate of UV to mid-IR, we identified a sample of 73 LBG candidates. Available data set of the GOODS-S (CDF-S) field covering the to the one used by Ly et al. (2009). Using the deep publicly more evolved and z/BX method, while also decreasing the number of or dust-reddened galaxies completely.

Our NUV-dropout technique allows for the detection of more evolved and/or dust-reddened galaxies not detected with the BM/BX method, while also decreasing the number of interlopers compared to the BzK method. Although the BM/BX and BzK methods can select much fainter objects than we can here, due to the limitation of GALEX in sensitivity, they exclude the more evolved and/or dust-reddened galaxies completely. The fact that 40% of the dropout-selected LBGs are not detected by the BM/BX and/or BzK methods provides for additional UV/optical-selected star formation at z ~ 2, especially if hidden by large amounts of dust.

We find that our z ~ 2 galaxy sample is consistent with LBGs at z ~ 3, and therefore allows for consistent follow-up studies at redshifts spanning z ~ 1.0–7.

We calculated useful photometric redshifts using HYPERZ and included a small set of spectroscopic redshifts for our LBG candidate sample (Figure 5, red filled circles). The normalized rms scatter for our LBG candidate sample is δzrusm = 0.198, with a smaller mean offset of ⟨dzoffset⟩ = 0.095.

Using the combination of spectroscopic (where available) and photometric redshifts, we fitted synthetic models from a library of PEGASE spectra to our LBG sample, and determined ages ranging from 4 Myr to 3 Gyr, masses between 9 × 10^8 M⊙ and 2 × 10^10 M⊙, and SFRs up to ~270 M⊙ yr⁻¹.

Our LBG candidates have moderate stellar masses and SFRs consistent with z ~ 3 LBGs (e.g., Shapley et al. 2005). Ages and dust extinction values of our sample are also more consistent with LBGs at z ~ 3, in comparison with the BX-selected galaxies at z ~ 2 of, e.g., Shapley et al. (2005), although our sample shows a lack of the very young star-forming galaxies found in the BM/BX and z ~ 3 samples (Figure 8). Our sample represents the moderate mass range of the UV luminosity distribution of LBGs at this redshift. This can lead to selection biases against objects with much higher masses. We should therefore exercise care when comparing our results to other surveys.

We also identified a small fraction of our LBG sample (~20%) as potential ILLBGs and/or submillimeter galaxies using Spitzer 8.0 and 24 μm data. Although there is some overlap with the other z ~ 2 LBGs, the R – [3.6] versus [3.6] plot in Figure 10 shows that the ILLBGs (blue and orange diamonds) represent the UV-bright end of the LBG distribution for a given value of R – [3.6]. Due to their red colors at optical wavelengths (compared to the BM/BX-selected), most of these galaxies are missed by the BM/BX and BzK methods (~10% detected).

The ILLBG SED fits result, on average, in higher total stellar masses, SFRs, and extinctions than our overall sample. Compared with higher and lower redshift LBGs from the literature, we find that our z ~ 2 sample has an average extinction which is higher than LBGs at z ~ 3 (e.g., Shapley et al. 2001; Verma et al. 2007; Yabe et al. 2009). A similar result holds in comparison with ILLBGs at z ~ 3 (e.g., Rigopoulou et al. 2006), with the exception of massive, IR-luminous, ULIRG-like LBGs which are selected in the IR (Shim et al. 2007). We find

Figure 11. Example images showing the morphological classification applied. The image size is 3′ × 3′. From left to right, and referring to galaxies by catalog number: disk-like (top row): 11800 (dropout-selected LBG), 7312 (dropout-selected ILLBG), 6039 (NUV-selected LBG), 7479 (NUV-selected ILLBG); compact (bottom row): 6633 (dropout-selected LBG), 12478 (dropout-selected LBG), 7312 (dropout-selected ILLBG), 10869 (NUV-selected LBG).
that the masses and extinction values are in better agreement with results for $z \sim 1$ LBGs (Nilsson et al. 2011).

The median total IR luminosity of our subsample of $L_{\text{TIR}} = 4 \times 10^{11} L_\odot$ indicates that these ILLBGs are comprised mainly of LIRGs. Only $\sim 15\%$ (2 out of 15 ILLBGs) are comparable to ULIRGs with $L_{\text{TIR}} \geq 10^{12} L_\odot$. From the total IR luminosities, we estimate a median SFR half that compared to the one derived from the SED model fits. The role of ILLBGs in the overall scheme of star formation at $z > 1.2$ and their contribution to the CIB merits further investigation, as ILLBGs could contribute significantly.

A simple morphological classification shows that the majority of our LBG candidates appear disk-like, and many show indicators for mergers and interactions. Similar results were found for the ILLBGs, with $\sim 80\%$ having disk-like morphologies. This is consistent with results published for $z \sim 1$ LBGs (Burgarella et al. 2006) and $z \sim 1$ LIRGs (e.g., Melbourne et al. 2005; Bell et al. 2005; Hammer et al. 2007).

Overall, our study shows that the selection of star-forming galaxies at $1.5 < z < 2.5$ using a true Lyman break dropout technique allows for the selection of a robust sample of LBGs, which can be used for comparable follow-up studies with LBGs at higher redshifts. A Lyman break selection like we used here allows redder, more massive LBGs to be included in comparison to other selection techniques such as the BM/BX and BzK methods.

This work is based on observations made with ESO Telescopes at the La Silla or Paranal Observatories under program ID 171.A-3045. Observations have been carried out using the Very Large Telescope at the ESO Paranal Observatory under Programme ID 168.A-0485. This work is also based in part to other selection techniques such as the BM/BX and BzK methods.

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