DEEP KECK \textit{u}-BAND IMAGING OF THE HUBBLE ULTRA DEEP FIELD: A CATALOG OF $z \sim 3$ LYMAN BREAK GALAXIES

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ABSTRACT

We present a sample of 407 $z \sim 3$ Lyman break galaxies (LBGs) to a limiting isophotal $u$-band magnitude of 27.6 mag in the Hubble Ultra Deep Field. The LBGs are selected using a combination of photometric redshifts and the $u$-band drop-out technique enabled by the introduction of an extremely deep $u$-band image obtained with the Keck I telescope and the blue channel of the Low Resolution Imaging Spectrometer. The Keck $u$-band image, totaling 9 hr of integration time, has a 1$\sigma$ depth of 30.7 mag arcsec$^{-2}$, making it one of the most sensitive $u$-band images ever obtained. The $u$-band image also substantially improves the accuracy of photometric redshift measurements of $\sim50\%$ of the $z \sim 3$ LBGs, significantly reducing the traditional degeneracy of colors between $z \sim 3$ and $z \sim 0.2$ galaxies. This sample provides the most sensitive, high-resolution multi-filter imaging of reliably identified $z \sim 3$ LBGs for morphological studies of galaxy formation and evolution and the star formation efficiency of gas at high redshift.

Key words: cosmology: observations – galaxies: distances and redshifts – galaxies: evolution – galaxies: general – galaxies: high-redshift – galaxies: photometry

Online-only material: color figures, machine-readable tables

1. INTRODUCTION

The Hubble Ultra Deep Field (UDF; Beckwith et al. 2006) provides the most sensitive high-resolution images ever taken, yielding a unique data set for studying galaxy evolution. These data have contributed to many scientific advances, including constraining the star formation efficiency of gas at $z \sim 3$ (Wolfe & Chen 2006), aiding in determining the luminosity function in the redshift range 4 $\lesssim z \lesssim 6$ (Bouwens et al. 2007), bringing insight into the merger fractions of galaxies (Conselice et al. 2008), and yielding the discovery of clumpy galaxies at high redshift (Elmegreen et al. 2007).

Knowledge of galaxy redshifts is essential to understanding their nature, and various approaches are used to estimate this key attribute. A number of studies identify objects in the redshift range 4 $\lesssim z \lesssim 6$ using the deep multi-filter (BVIZJH) UDF images by identifying so-called “dropout” galaxies which are detectable in certain broadband filters but not in others (Beckwith et al. 2006; Bouwens et al. 2006, 2007). Others use photometric redshifts derived across the entire redshift range 0 $\leq z \leq 6$ by analyzing the colors of galaxies in a wider range of filters (Coe et al. 2006). This latter approach has the potential to provide relatively accurate ($\sigma_{\Delta z/(1+z)} \lesssim 0.1$, Fernández-Soto et al. 2001) redshift estimates for a large number of galaxies in a given field, but traditionally has serious problems producing accurate results near $z \sim 3$, a redshift range for which key spectral energy distribution (SED) features fall blueward of the previously available filter set.

The majority of galaxies observed at $z \sim 3$ are Lyman break galaxies (LBGs): star-forming galaxies that are selected based on the break in their SED at the 912 Å Lyman limit primarily by interstellar gas intrinsic to the galaxy, as well as a flux decrement shortward of 1216 Å in the galaxy rest frame due to absorption by the Lyman series of optically thick hydrogen gas along the line of sight. This Lyman limit discontinuity in the SED significantly dims these galaxies shortward of $\sim3500$ Å, allowing them to be found with the $U$-band dropout technique (Steidel & Hamilton 1992; Steidel et al. 1995, 1996a, 1996b). Previously, the available observations in the UDF did not include deep $u$-band imaging. The next prominent broadband signature in the SED is the 4000 Å break, which is redshifted to the near-infrared (IR) for $z \sim 3$ LBGs. Without the $u$ band or very deep IR coverage, it is very difficult to determine from broadband imaging alone whether the observed decrement in the SED near the observed frame $\sim4800$ Å is a low-redshift galaxy with a 4000 Å break, or a high-redshift galaxy with a decrement from the 1216 Å break. This degeneracy causes “catastrophic” errors in the photometric redshifts of galaxies at $z \sim 3$ without $u$-band data (Ellis 1997; Fernández-Soto et al. 1999; Benítez 2000).

The purpose of this paper is to present a reliable sample of LBGs at $z \sim 3$ in the UDF through the introduction of ultra-deep $u'$-band imaging acquired with the 10 m Keck I telescope. The Keck I telescope and the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995; McCarthy et al. 1998) form an ideal combination to probe galaxies at the $z \sim 3$ epoch due to the light-gathering power of the 10 m primary mirror and the outstanding efficiency of the LRIS blue channel in the near UV. This allows the $u$-band filter (with effective wavelength $\lambda_{\text{eff}} \approx 3400$ Å, FWHM $\approx 690$ Å) used with the blue arm (LRIS-B) to be $\sim300$ Å bluer and $\sim360$ Å wider than the $u$-band filter on the Visible Multi-Object Spectrograph (VIMOS; Fevre et al. 2003) instrument ($\lambda_{\text{eff}} \approx 3700$ Å, FWHM $\approx 330$ Å) at the Very Large Telescope (VLT) and still be effective. Consequently, this enables us to probe the Lyman break efficiently to a lower limit of $z \sim 2.5$, versus the VIMOS limit of $z \sim 2.9$ as shown by the VIMOS observations of GOODS-South by Nonino et al. (2009). In addition, although the UDF field can only be observed at high air mass from Mauna Kea, the total throughput of LRIS-
B and its bluer \( u \) band is approximately twice that of VIMOS with its redder \( u \) band. This gives Keck the unique ability to select lower redshift LBGs via their Lyman break.

We assemble a reliable sample of LBGs in the UDF with a combination of the \( U \)-band dropout technique and photometric redshifts, and provide photometric redshifts for all galaxies with good \( u \)-band photometry. We find that the \( u \)-band imaging improves the photometric redshifts of \( z \sim 3 \) galaxies by reducing the degeneracy between low- and high-redshift galaxies. Furthermore, the combination of deep LRIS \( u \) band and high-resolution multiband Hubble Space Telescope (HST) imaging provides an unprecedented view of \( z \sim 3 \) LBGs to improve our understanding of their highly irregular rest-frame UV morphologies (Law et al. 2007) down to unprecedented depths.

The deep, high-resolution LBG sample will also extend current constraints on the star formation efficiency of gas at \( z \sim 3 \). Reservoirs of neutral gas are needed to provide the fuel for star formation. Damped Ly\( \alpha \) systems (DLAs), selected for their neutral hydrogen column densities of \( N_{\text{HI}} \geq 2 \times 10^{20} \text{cm}^{-2} \), dominate the neutral-gas content of the universe in the redshift interval \( 0 < z < 5 \). DLAs contain enough gas to account for \( 50\% \) of the mass content of visible matter in modern galaxies (see Wolfe et al. 2005, for a review) and may act as neutral-gas reservoirs for star formation, since stars form when local values of the \( \text{H}_1 \) column density, \( N_{\text{HI}} \), exceed a critical value. At high redshift, the star formation rate (SFR) is assumed to follow the Kennicutt–Schmidt (KS) law (established for nearby galaxies) which states how the SFR per unit physical area, \( \Sigma_s \), relates to the neutral gas (i.e., \( \text{H}_1 \) and \( \text{H}_2 \)) column density: \( \Sigma_s \propto N_{\text{HI}}^{1.4} \) (Kennicutt 1998). Strong DLAs with \( N_{\text{HI}} \geq 1.6 \times 10^{21} \text{cm}^{-2} \) in the redshift range \( 2.5 < z < 3.5 \) are predicted to have emission from star formation in the rest-frame UV redshifted into the optical such that they are detectable in the UDF F606W image. Wolfe & Chen (2006) searched for low-surface-brightness emission from DLAs in the UDF and found the in situ SFR efficiency of DLAs to be less than \( 5\% \) of the KS law. In other words, star formation must occur at much lower rates in DLAs at \( z \sim 3 \) than in modern galaxies. Whereas the Wolfe & Chen (2006) results set sensitive upper limits on in situ star formation in DLAs excluding known galaxy regions, no such limits exist for DLAs containing LBGs. The sample presented here enables a search for spatially extended low-surface-brightness emission around \( z \sim 3 \) LBGs which will yield constraints on the star formation efficiency at high redshift (M. Rafelski et al. 2009, in preparation). This is one of the main motivations for constructing this sample, and therefore we construct our sample conservatively to minimize the number of potential interlopers.

We present our catalog of \( z \sim 3 \) LBGs, provide photometric redshifts for the entire sample of objects that have reliable \( u \)-band photometry, and make the \( u \)-band image available to the public. The observations are described in Section 2, and the data reduction and analysis in Section 3. We discuss the photometric selection of \( z \sim 3 \) galaxies in Section 4, and summarize our major findings in Section 5. Throughout this paper, we adopt the AB magnitude system and an (\( \Omega_M, \Omega_{\Lambda}, h \) = (0.3, 0.7, 0.7)) cosmology with parameters \( \Gamma = 0.21, n = 1 \), which are largely consistent with recent values (Hinshaw et al. 2009).

2. Observations

The \( u \)-band (\( \lambda_u \sim 3400 \text{ Å} \), FWHM \( \sim 690 \text{ Å} \)) images of the UDF (\( \alpha(J2000) = 03^h32^m39^s, \delta(J2000) = -27^\circ47'29^\prime1 \)) were obtained with the 10 m Keck I telescope using the LRIS. The \( u \)-band data were taken with the new Cassegrain Atmospheric Dispersion Corrector (Cass ADC; Phillips et al. 2006) to minimize image distortions from differential atmospheric refraction. The Cass ADC was critical to the success of these observations because of the low elevation of the UDF from Mauna Kea, and the blue wavelength of our primary band. The data also benefit from the backside illuminated, dual UV-optimized Marconi 2048 x 4096 pixel CCDs on LRIS-B, with 0′:135 pixels and very high UV quantum efficiency (\( \sim 50\% \) at \( \lambda_o \sim 3450 \text{ Å} \)). Because the quantum efficiency of the two CCD chips varies \( \sim 30\%-35\% \) in the \( u \) band, we placed the UDF entirely on the more sensitive chip (CCD1). We used a dichroic beam splitter (D460) to simultaneously observe the \( u \) band on the blue side, and the \( V \)-band and \( R \)-band on the red side. The red channel data were taken for astrometric and photometric consistency checks, and were not used in this study other than for calibration purposes due to the much deeper and higher resolution UDF images available over those wavelength ranges.

The observations were carried out in dark time over two runs, 2007 October 7–9 (three half nights) and 2007 December 3–4 (two half nights). We lost the entire first night of the first run to weather, and had moderate weather and seeing conditions throughout both runs that yielded a median seeing FWHM of \( \sim 1.3 \) in the \( u \) band. In order to maximize time on sky, we adopted the dither strategy of Sawicki & Thompson (2005, see their Equation (1)), setting the red channel exposure times such that the last readout of the red channel coincided with the end of the blue channel readout. The \( u \)-band images were acquired as a series of 36 x 900 s exposures to avoid the nonlinear regime of the CCD, totaling 9 hrs of integration time on target. We executed a nine-point dither pattern with 10′′ dithers to deal with bad pixels and to create a super-sky flat.

The UDF can only be observed at large air masses at Mauna Kea, which can affect the shape of the \( u \)-band throughput. We show a histogram of our observed air masses and the variation of the filter throughput with different air masses in Figure 1. We find that the variations in air masses in our sample do not significantly affect the blue side cutoff of our filter. Specifically, we find that the variation between our best and worst air masses yields a change in \( \lambda_o \) \( \lesssim 10 \text{ Å} \), with typical changes in \( \lambda_o \) being \( \lesssim 5 \text{ Å} \). Given the small variation of \( \lambda_o \), we derive the final \( u \)-band filter transmission curve by convolving the measured filter throughput with the atmospheric attenuation at our average air mass of 1.57 and the CCD quantum efficiency.

Throughout the paper, we utilize the \( B \), \( V \), \( \iota \), and \( z' \) band (F435W, F606W, F775W, and F850LP, respectively) observations of the UDF (Beckwith et al. 2006), obtained with the Wide Field Camera (WFC) on the HST Advance Camera for Surveys (ACS; Ford et al. 2002). These images cover 0.8 arcmin\(^2\), although we prune our catalog to the central 11.56 arcmin\(^2\) which contains at least half the average depth of the whole image and overlaps our \( u \)-band image with uniform depth. In addition to these ACS images, we also include observations taken with the NICMOS camera NIC3 in the \( J \) and \( H \) bands (F110W and F160W; Thompson et al. 2006). These red wavelengths cover the central 5.76 arcmin\(^2\) of the UDF, so we only use them whenever the field of view (FOV) overlaps. Figure 2 plots the total throughput of the filters used in this paper: the Keck LRIS-B \( u \) band, the HST ACS \( B \), \( V \), \( \iota \), and \( z' \) bands, and the HST NICMOS \( J \) and \( H \) bands, and include the CCD quantum efficiency and atmospheric attenuation.
3. DATA REDUCTION AND ANALYSIS

3.1. Image Processing

The LRIS-B data were processed in a combination of custom code in IDL, and standard data reduction algorithms from IRAF. The images were bias subtracted, first from the overscan region and then from separate bias frames to remove any residuals, before being trimmed to remove any vignetted regions of LRIS. Super-sky flats were created using IRAF from the median of all the unregistered images with sigma clipping to remove objects and cosmic rays, which were then used to flats the images. These prove superior to dome and twilight sky flats in determining the CCD response in the u-band because of the short wavelengths, and yield excellent flats. Dithering offsets were determined using custom code and SExtractor (Bertin & Arnouts 1996) to locate bright objects common to all the images. In order to drizzle (Fruchter & Hook 2002) only once and keep correlated noise to a minimum, the images were distortion corrected using the solution provided by J. Cohen & W. Huang (2008, private communication) and shifted to correct for the dithering offsets all at once using the geotran package in IRAF. We drizzled with pixfrac = 0.5 to improve the point-spread function (PSF) and set the pixel scale such that the pixels are integer multiples of the UDF pixels, 0.12", for reasons explained in Section 3.4. To maximize the signal-to-noise ratio (S/N), the images were weighted by their inverse variances. The drizzled images were then combined using the IRAF task imcombine, with sigma clipping to remove bad pixels and cosmic rays. These images were trimmed to include regions of uniform depth (11.56 arcmin²), normalized to an effective exposure time of 1 s, and then background subtracted using the global background determined with SExtractor. An astrometric solution was applied with the IRAF task cccmap by matching bright and nearly unresolved objects in the UDF to those in the final stacked image. The final rms astrometric errors are between 0.02 and 0.03, negligible in comparison to the 1.3 FWHM of the u-band PSF.

3.2. Photometric Calibration

Moderate weather yielded no completely photometric night for our calibration, and we therefore calibrated to the Multi-wavelength Survey by Yale–Chile (MUSYC; Gawiser et al. 2006), which covers the same part of the sky as our primary observations. We include all our filters (u, V, and R) for this calibration. All our calibrations are in the AB95 system of Fukugita et al. (1996), hereafter referred to as AB magnitudes. We used the IRAF tasks phot and fitparams to solve for zero-point magnitudes, air-mass correction coefficients, and appropriate color correction coefficients. Specifically, we use the equation:

\[ m = -2.5 \log_{10}(F) + Z - cX - Y \]

where \( F \) is the flux in counts/s, \( z \) is the zero-point magnitude, \( c \) is the air-mass coefficient, \( X \) is the air mass, and \( Y \) is the color term. We allow a color term to account for any differences between the U filter used by MUSYC and the u-band filter in our observations, similar to the color term used by
Gawiser et al. (2006) to correct for their differences compared to the Johnson-Cousins filter set. The galactic extinction of 0.0384 is subtracted from the zero-point magnitude, using the relation \( A(\nu) = 4.8E(B-V) \) interpreted from Cardelli et al. (1989), where \( E(B-V) = 0.008 \) (Beckwith et al. 2006). The final results for the \( u \)-band calibration are a zero-point magnitude \( Z = 27.80 \pm 0.03 \), an air-mass coefficient term \( c = 0.41 \), an average air mass \( X = 1.57 \), and a color term \( Y = (0.13 \pm 0.02) \times (U - B)_{\lambda AB} \). We double check our calibration using multiple observed photometric standard stars (Landolt 1992) over a range of air masses, and the zero-point and air-mass correction coefficients are consistent with those found when calibrating to the MUSYC catalog. As a result, we are confident that the \( u \)-band image is well calibrated.

### 3.3. Depth of the \( u \)-band Image

It is useful to characterize the depth of the \( u \)-band image, however, different definitions exist to describe the sensitivity of an image. Two commonly quoted limits are presented here: a measurement of the sky fluctuations of the image, and a limiting magnitude corresponding to a 50% decrease in object counts through Monte Carlo simulations.

The sky noise of the image is measured via the pixel-to-pixel rms fluctuations in the image, best measured by fitting a Gaussian to the histogram of all pixels without sources. Sources are identified with the program SExtractor, with the threshold set such that the negative image has no detections. This yields a depth of 31.0 mag arcsec\(^{-2}\), 1\( \sigma _u \) sky fluctuations. However, since the image is drizzled, correlated noise between the pixels is introduced. The theoretical increase in noise due to \( \text{pixfrac} = 0.5 \) using Equation (10) from Fruchter & Hook (2002) is 20%. Alternatively, the correlated noise can be estimated empirically with Equation (2) from Fernández-Soto et al. (1999), which uses a covariance matrix to determine a small overestimate of the real error.\(^6\) This results in a slightly more conservative depth of 30.7 mag arcsec\(^{-2}\), 1\( \sigma _u \) sky fluctuations, which is what we quote here.

Additionally, to get a better sense of the usable depth of the image, a limiting magnitude is often quoted (e.g., Chen et al. 2002; Sawicki & Thompson 2005). We define \( u \)\( \text{lim} \) as the magnitude limit at which more than 50% of the objects are detected. The best way to determine \( u \)\( \text{lim} \) is through Monte Carlo simulations, which take into account both the sky surface brightness and the seeing in our image. Since our image PSF has more flux in the wings than a Gaussian, we plant both Gaussian objects, and objects modeled to fit our PSF using a two-dimensional (2D) Moffat profile.\(^7\) The custom IDL code was used to extract bright unresolved objects in the \( u \)-band image, take the median of all these objects, and create a composite object stack. The composite image was then fit both by a Gaussian and by a 2D Moffat profile using MPFIT (Markwardt 2009), with a modification to ensure that the wings of the profile go to 0 for the Moffat profile. We semi-randomly insert these objects with a range of fluxes into the \( u \)-band image. The locations of the planted objects are constrained such that they do not: (1) fall off the edges, (2) fall on a real detected object, and (3) fall on any previously planted objects. We find a total \( u \)\( \text{lim} \) of 27.3 mag for the Gaussian and 27.2 mag for the Moffat profile (see Figure 3), where the total magnitudes are based on SExtractor’s mag\(_\text{auto}\) apertures, which are Kron-like (Kron 1980) elliptical apertures corrected for possible contamination. While total magnitudes are generally reported, isophotal apertures are more appropriate for LBGs, and yield a \( u \)\( \text{lim} \) of 27.7 mag for the Gaussian and 27.6 mag for the Moffat profile. This is one of the deepest \( u \)-band images ever obtained, with our sensitivity being similar to those reported in the Keck Deep Fields (Sawicki & Thompson 2005).

This detection method does not match the detection method used in Section 3.4, and therefore does not constrain our detection efficiency of LBGs. As explained below, we use our prior knowledge of the positions of the sources which yields a different completeness limit. However, this result gives the depth of our \( u \)-band image for comparison to other studies.

### 3.4. Photometry Through Template Fitting

In order to obtain robust colors across images with varied PSFs, it is necessary to match apertures and correct for PSF differences. If the difference is minor, then methods to apply aperture corrections to account for the variations are appropriate, such as the ColorPro software by Coe et al. (2006). However, such algorithms don’t perform well when the difference in the PSF FWHM is large, such as when combining the high-resolution data from the HST (0′.09 FWHM) with the low-resolution images obtained in this study with Keck (1′.3 FWHM). In this case, the uncertainties in aperture corrections are unreasonably large, and the low-resolution images are crowded such that objects overlap, making object definitions that are valid in both high and low-resolution images difficult to determine.

In order to avoid these uncertainties, we use the TFIT (Laidler et al. 2007) template-fitting method that uses prior knowledge of the existence, locations, and morphologies of sources in the deeper high-resolution UDF images to improve the photometric measurements in our low-resolution \( u \)-band image. This method

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\(^6\) The equation has a typographic error. The sum should be over \( i_1, i_2 = 1 \) to \( i_1, i_2 = 3 \).

\(^7\) The Moffat profile (Moffat 1969) is a modified Lorentzian with a variable power-law index that takes into account the flux in the wings of the intensity profile which are not included in a Gaussian profile.
creates a template of every object by convolving each object in the high-resolution image with the PSF of the low-resolution image. These templates are then fit to the low-resolution image to determine the flux of all the objects in the \( u \) band, relative to the flux in the UDF \( V \)-band image. We chose the \( V \)-band as the high-resolution reference image because it is closest in wavelength to the \( u \) band, without being affected by the Ly\( \alpha \) forest over the redshift interval \( 2.5 \lesssim z \lesssim 3.5 \). The result is a very robust color which relates every object in the high-resolution \( V \)-band image to the low-resolution \( u \) band, avoiding the problem of aperture matching between the two images while intrinsically correcting for the PSF difference. Using the \( V \)-band flux, the color is converted to a \( u \)-band flux, which inherits the same isophotal aperture as the high-resolution \( V \)-band image.

The aperture correction used to obtain total fluxes for the \( V \)-band image is then also valid to obtain total fluxes for the \( u \) band. For a more in-depth explanation, see Laidler et al. (2007).

We chose to use TFIT as it is publicly available, well documented, and its performance is carefully tested. Like all the other methods, there are some constraints that had to be met to use this algorithm. The first is that the pixel scale of the \( u \)-band image must be an integer multiple of the pixel scale of the UDF \( V \)-band image. This was accomplished by drizzling the images such that the pixel scale of the \( u \) band is four times larger than the \( V \)-band, as mentioned in Section 3.1. The second and third requirements are that the images must not be rotated with respect to each other, and the corner of the \( V \)-band image must coincide with the corner of the \( u \)-band image. These two requirements were met by rotating and trimming the \( V \)-band image using IDL. The resultant image was compared to the original image, and the difference in photometry was negligible compared to the intrinsic uncertainties. We also improved our fit by source weighting the rms map before providing it to the TFIT pipeline, as suggested by Laidler et al. (2007).

In order to avoid proliferating different catalogs with minor differences in object definitions, we adopt the object definitions of Coe et al. (2006). These definitions include the catalogs of Beckwith et al. (2006) and Thompson et al. (2006), as well as detections performed on a white light image by Coe et al. (2006). By using identical object definitions as Coe et al. (2006), we can use the careful photometry for the \( B, V, i', z', J, \) and \( H \) bands already determined, and compare our redshift determinations knowing we have used identical apertures.

TFIT requires a SExtractor catalog of the \( V \)-band image as an input to the pipeline. The program ssexag (Coe et al. 2006) was run on the segmentation map of Coe et al. (2006) to provide the necessary information to TFIT while using the desired object definitions of Coe et al. (2006). The segmentation map defines which pixels belong to each identified \( V \)-band object. The ssexag program forces SExtractor to run using a predefined segmentation map (for details, see Coe et al. 2006). TFIT also requires a representative 2D model of the \( u \)-band PSF, and is sensitive to the quality of its construction. We use the same Moffat profile fit described in Section 3.3 to model the PSF of the \( u \)-band image, and then use this as the transfer kernel by TFIT to convolve the \( V \)-band galaxy cutouts. We note that there is no significant spatial variation of the PSF across the field.

In general, the higher the resolution and sensitivity of the high-resolution image, the better TFIT can model the sources for the low-resolution image. If an input catalog is not complete enough, then unmodeled objects can act as an unsubtracted background, slightly increasing the flux of all objects (Laidler et al. 2007). However, this has a limit, and eventually there are so many sources that are too faint to detect in the low-resolution image that galaxies are not well constrained given the substantial number of priors. This yields a large number of galaxies with unconstrained fluxes that increase the uncertainties of the nearby objects without yielding any new information. The UDF \( V \)-band image has substantially higher resolution and is deeper than the \( u \)-band image, and therefore a limit was put on the faintest galaxy used as a prior in TFIT. Only galaxies brighter than \( V = 29 \) mag are included in the input catalog to TFIT. The galaxies fainter than \( V = 29 \) mag are too faint to be constrained by the \( u \) image, and only add noise to the TFIT results. We stress that this is a conservative cut, and does not introduce an unsubtracted background.

The quality of the resulting photometric fits can be evaluated through Figure 4, which depicts four panels: the \( V \)-band image from the UDF, the \( u \) image from Keck, the model image, and the residual image. The model and residual images are diagnostics produced by TFIT, and are not used in the fitting process. The model image is a collage of the \( V \)-band galaxies convolved with the PSF of the \( u \)-band image, scaled by the TFIT flux measurement for each object. The residual image is the difference of the model and the \( u \)-band images. Ideally, the residual image would be zero, but this is not the case (especially for bright objects), with multiple effects contributing to the imperfect residual. For instance, if the object in the \( V \)-band image is saturated, then it has the wrong profile for the \( u \) band and leaves a residual. Alternatively, imperfections in the modeled PSFs when scaled to large flux measurements of bright objects will also leave a residual. This effect was minimized by using a source-weighted rms map, although photometry of the brightest objects are imperfect. In practice, it is very difficult to perfectly align two images, the distortion correction is not perfect, and images generally have spatially varying PSFs. To minimize these affects, TFIT does a "registration dance," where it cross correlates each region of the model with the region of the data to find any local shifts. This registration dance was performed, which slightly improved the residual image, and leads to more robust photometry.

3.5. Sample Selection

Our aim is to identify a sample of high-redshift galaxies that are suitable for constraining the star formation efficiency of gas at \( z \sim 3 \). A large fraction of objects for which fluxes are measured with TFIT are too faint to yield sufficient information regarding the object’s redshift, and we therefore limit our sample to those objects with high \( S/N \). We select objects based on their \( V \)-band magnitudes, since cuts in \( u \) band would preferentially remove LBGs. The median \( u \)-band \( S/N \) of all objects decreases as a function of the \( V \)-band magnitude and drops below \( 3 \sigma \) at \( V \gtrsim 27.6 \) mag. We adopt this \( V \)-band magnitude cut to include the majority of high \( S/N \) \( u \) objects, while removing \( S/N < 3 \) objects. We note that this is a conservative \( 3 \sigma \) cut since most LBGs won’t be detected in the \( u \) band reducing the overall median \( S/N \).

In addition to removing low \( S/N \) objects, we wish to remove objects with photometry affected by nearby neighbors. TFIT can identify such objects with the covariance index diagnostic
that uses the covariance matrix (Laidler et al. 2007). During the fitting of an object’s photometry as described in Section 3.4, TFIT uses the singular value decomposition routine to perform a chi-square ($\chi^2$) minimization. This yields a covariance matrix which is used to calculate uncertainties via the square root of the variance (the diagonal element), as well as the covariance (the off-diagonal elements) of all objects in the fit. The covariance index is the absolute value of the ratio of the off-diagonal and the diagonal elements (Laidler et al. 2007). The maximum value of the covariance index is saved, along with the corresponding object ID, and yields information about how an object’s photometry is affected by its most influential neighbor. Objects for which this ratio is much less than 1 are generally isolated objects, while objects with large covariance index values can have unreliable photometry. Multiple cuts are implemented to remove objects whose photometry have been significantly affected. First, all objects with a covariance index greater than 1 are cut because their measurements are not considered reliable. All remaining objects are kept if one of two conditions apply: either they have a covariance index less than 0.5, or they have a V-band flux greater than twice that of the nearest neighbor. This approach balances the desire for a large sample with the need to obtain reliable photometry. Lastly, we only consider objects that are detected in all four ACS bands ($B$, $V$, $i'$, and $z'$) to facilitate and improve color selection in Section 4.2. This requirement removes most galaxies at $z > 4$ as they have little flux in the $B$ or redder bands.

Table 1 lists the 1457 galaxies that are left after the V-band magnitude, covariance index, and V-band flux ratio cuts. Each entry includes the object ID (matching those from Coe et al. 2006), R.A., decl., $u$ magnitudes and uncertainties, and $u$/S/N. It also lists information regarding the most significant neighbor, namely, its object ID, covariance index, V-band flux ratio, and separation distance. The $u$ magnitude uncertainties include the uncertainties due to the $V$-band aperture correction made in Coe et al. (2006), as the accuracy of our $u$ magnitudes depend on the accuracy of the $V$-band magnitudes. Objects that are observed with a $u$-band flux less than $3\sigma$ significance are considered undetected in the $u$ band and are assigned a $3\sigma$ upper limit. The magnitude limit is set to

$$m_{3\sigma} = -2.5\log_{10}(3\sigma_{\text{TFIT}}) + Z_{\text{LRIS}},$$

where $Z_{\text{LRIS}}$ is the zero-point magnitude. The error distribution from TFIT is normally distributed and the upper limits from TFIT are robust, as evaluated in Laidler et al. (2007).
4. PHOTOMETRIC SELECTION OF \( z \sim 3 \) GALAXIES

Star-forming galaxies early in their history, such as LBGs, exhibit a clear break in their Spectral Energy Distribution (SED) at the 912 Å Lyman limit (Lyman break), as well as multiple absorption lines shortward of 1216 Å by the Lyman series. Photons bluer than the Lyman limit are not observed because the interstellar gas intrinsic to the galaxy and components of the foreground gas along the line of sight of the galaxy are optically thick at \( \lambda \lesssim 912 \) Å. At a redshift of \( \gtrsim 2.5 \), these spectral features are redshifted to optical wavelengths, with the Lyman break entering the \( u \) band (\( \sim 3500 \) Å). The ability to observe the Lyman break optically allows large samples of high-redshift galaxies to be identified based on multicolor photometry where LBGs are selected by a strong flux decrement shortward of the Lyman limit, and a continuum longward of the Lyman limit and a continuum longward of the Lyman limit, and a continuum longward of the Lyman limit. 

Although color selection and photometric redshifts utilize the Balmer break at 3646 Å, and the more pronounced 4000 Å absorption lines shortward of 1216 Å by the Lyman series. Absorption lines shortward of 1216 Å by the Lyman series. Absorption lines shortward of 1216 Å by the Lyman series. Absorption lines shortward of 1216 Å by the Lyman series. Absorption lines shortward of 1216 Å by the Lyman series.

4.1. Photometric Redshifts

Photometric redshifts (hereafter, photo-\( z \)'s) are a well known and robust procedure to determine redshifts of galaxies when spectra are unavailable (e.g., Koo 1985; Lanzetta et al. 1998; Benítez 2000; Coe et al. 2006; Hildebrandt et al. 2008). They have the advantage over color selection that they take into account all the colors available simultaneously in \( \chi^2 \) fits to template SEDs and yield more precise redshift information with clear redshift confidence limits. The photo-\( z \)'s also sample \( z \sim 3 \) galaxies in regions of color space that color-selected samples avoid because of low-redshift galaxies, and therefore can provide a larger sample. However, photo-\( z \) uncertainties do not always include systematic errors caused by variations and evolution of galaxy SEDs compared to SED templates, and possible mismatches of SED templates (see Section 4.1.2). Such systematic problems and the lack of a large spectroscopic sample make it difficult to characterize the contamination fraction of photo-\( z \)-selected \( z \sim 3 \) galaxies (see Section 4.1.3). Nonetheless, they provide the largest sample of LBGs for study.

For each galaxy, photo-\( z \) codes produce a probability distribution function, \( P(z) \), representing the probability of a galaxy being at any specific redshift. However, the \( P(z) \) can have multiple peaks, especially at \( z \sim 3 \) where there is a degeneracy with galaxies at \( z \sim 0.2 \), which then translates into large uncertainties for the photo-\( z \) (Benítez 2000). The introduction of the \( u \) band data helps resolve the photo-\( z \) degeneracy and improve the photo-\( z \) fits for \( z \sim 3 \) galaxies as it targets the most dominant signature in their SED, the Lyman break. We present photo-\( z \)'s for the entire sample of galaxies with \( u \) band data from Section 3.5 in Table 2, but caution against using them blindly to select galaxies at \( z \sim 3 \). We recommend making cuts on the sample to select galaxies with good \( \chi^2_{\text{mod}} \) and ODDS (for a description of these parameters, see Section 4.1.1).

4.1.1. Bayesian Photometric Redshifts

There are many different photo-\( z \) codes available, and Hildebrandt et al. (2008) explain the benefits of the different algorithms. We chose to use the Bayesian photo-\( z \)'s (BPZ) (Benítez 2000; Benítez et al. 2004; Coe et al. 2006) to be consistent with past photo-\( z \)'s determined for the UDF without \( u \) band data (Coe et al. 2006). Hildebrandt et al. (2008) advise using the SED templates supplied with their respective codes, since user-supplied SED templates can cause problems. However, a re-calibration of the SED template set improves the performance of the photo-\( z \)
redshifts, and we use the re-calibrated SED templates from Benítez et al. (2004) and Coe et al. (2006) that have been extensively tested with BPZ. These re-calibrated SEDs are based on the star-forming (Im), spiral (Scd, Sbc), and elliptical (E) galaxy templates from Coleman et al. (1980), the star bursting galaxy templates with different reddening (SB2, SB3) from Kinney et al. (1996), and the faint blue galaxy SEDs with ages of 25 and 5 Myr and metallicities of Z = 0.08 without dust from Bruzual & Charlot (2003), described in section Section 4.1 of Coe et al. (2006). We interpolate between adjacent galaxy SED templates for an additional two SED templates in the photo-z fit, similar to Benítez et al. (2004) and Coe et al. (2006).

SED templates are not always a good match for each specific galaxy, and when it is not possible to get a good fit to the SED template, then the resulting redshift may not be accurate. As a diagnostic of the goodness of fit, the BPZ code provides a reduced chi-square ($\chi^2_v$) value. However, high $\chi^2_v$ values do not always indicate an unreliable redshift. Bright galaxies with small photometric uncertainties will have larger $\chi^2_v$ values than faint galaxies with larger photometric uncertainties for the same numerator in $\chi^2$ (also known as the variance), yet have more reliable redshifts (see Figure 21 in Coe et al. 2006). This problem occurs because the systematic uncertainties of the SED templates are not taken into account, making $\chi^2_v$ no longer represent the relative quality of the fit. Nonetheless, a mechanism to evaluate the quality of the fits is required to trim the sample to reliable redshifts. To this end, Coe et al. (2006) introduce a modified reduced chi square ($\chi^2_{mod}$) value that assigns an uncertainty to the SED templates in addition to the uncertainty in the photometry of the galaxy. For clarity, we reproduce the equation from Coe et al. (2006) here:

$$\chi^2_{mod} = \sum_a \frac{(f_a - f_{T_a})^2}{\sigma_{f_a}^2 + \sigma_{f_T}^2} / \nu,$$

where $f_a$ are the observed fluxes, $\sigma_{f_a}$ is the error in observed fluxes, and $f_{T_a}$ are the model fluxes, normalized to the observed fluxes. $\sigma_{f_T}$ represent the model flux errors, which are set by Coe et al. (2006) to $\sigma_{f_T} = \max(f_a) / 15$. While the definition of $\sigma_{f_T}$ is arbitrary, it was picked such that the resultant $\chi^2_{mod}$ is a more realistic measure of the goodness of fit. This is especially important for bright galaxies, as uncertainties in the templates dominate the error budget, and the $\chi^2_v$ values are not useful. The reported $\chi^2_{mod}$ values are reduced chi square values, obtained by dividing by the number of degrees of freedom, $\nu$. The number of degrees of freedom is the difference between the number of filters observed and the number of parameters (in this case there are three fit parameters, redshift, template, and amplitude). The minimum number of filters used is 5 and the maximum is 7, so the range of $\nu$ in our study is $2 \leq \nu \leq 4$. We note that $\chi^2_{mod}$ is calculated after the photo-z determinations, and does not affect $P(z)$.

If the quality of the fit to the SED template is good, then the ODDS parameter is useful in measuring the spread in $P(z)$. A galaxy with high ODDS has a single peak in $P(z)$, while multiple or very wide peaks yield low ODDS. In general, restricting the photometric sample to those objects with ODDS $>$ 0.9–0.99 yield clearly defined redshifts (Benítez 2000; Benítez et al. 2004; Coe et al. 2006). In this paper, we are conservative and restrict our sample to objects with the best values of ODDS, those with ODDS $>$ 0.99. Additionally, selecting galaxies based on SED template type ($t_b$) can be useful when selecting a specific type of galaxy, where $1 = $El_cw, $2 = $Scd_cw, $3 = $Sbc_cw, $4 = $Im_cw, $5 = $SB3_kin, $6 = $SB2_kin, $7 = $25 Myr, and $8 = $5 Myr. For instance, in selecting LBGs we constrain ourselves to galaxies with $t_b > 3$, which only include star-forming galaxy templates. The redshifts, redshift uncertainties for a 95% confidence interval, $t_b$, ODDS, $\chi^2_v$, and $\chi^2_{mod}$ are all tabulated in Table 2.

| ID | $z^b_{ID}$ | $t_b^c$ | ODDS | $\chi^2_{mod}$ | $z_b^f$ | $t_b^f$ | ODDS1$^b$ | $z_b^2$ | ODDS2$^b$ |
|----|------------|---------|-------|----------------|--------|--------|----------|--------|----------|
| 1  | 0.17$^{+0.11}_{-0.12}$ | 3.00 | 1.000 | 16.40 | 0.20 | 0.17$^{+0.07}_{-0.07}$ | 3.00 | 1.000 | ... | ... | ... |
| 7  | 0.01$^{+0.10}_{-0.01}$ | 6.67 | 0.990 | 7.59 | 0.49 | 0.01$^{+0.10}_{-0.01}$ | 6.67 | 0.990 | 1.81$^{+0.02}_{-0.02}$ | 6.00 | 1.000 |
| 8  | 0.52$^{+0.15}_{-0.15}$ | 1.00 | 1.000 | 21.81 | 0.01 | 0.52$^{+0.07}_{-0.08}$ | 1.00 | 1.000 | ... | ... | ... |
| 13 | 0.43$^{+0.14}_{-0.14}$ | 3.33 | 1.000 | 8.00 | 0.21 | 0.43$^{+0.11}_{-0.08}$ | 3.33 | 1.000 | ... | ... | ... |
| 14 | 0.54$^{+0.15}_{-0.15}$ | 2.33 | 1.000 | 46.40 | 0.06 | 0.54$^{+0.07}_{-0.08}$ | 2.33 | 1.000 | ... | ... | ... |
| 15 | 0.52$^{+0.15}_{-0.16}$ | 1.67 | 0.970 | 1.98 | 0.09 | 0.52$^{+0.03}_{-0.12}$ | 1.67 | 0.520 | 0.57$^{+0.10}_{-0.02}$ | 2.00 | 0.443 |
| 22 | 3.23$^{+0.41}_{-0.41}$ | 5.00 | 0.999 | 7.34 | 0.44 | 3.23$^{+0.10}_{-0.29}$ | 5.00 | 0.977 | 2.90$^{+0.04}_{-0.10}$ | 3.33 | 0.023 |
| 24 | 1.39$^{+0.72}_{-0.78}$ | 7.00 | 0.363 | 1.56 | 1.68 | 1.39$^{+0.12}_{-0.13}$ | 7.00 | 0.247 | 1.65$^{+0.22}_{-0.14}$ | 6.67 | 0.429 |
| 33 | 0.78$^{+0.17}_{-0.13}$ | 3.67 | 1.000 | 1.96 | 0.08 | 0.78$^{+0.09}_{-0.09}$ | 3.67 | 1.000 | ... | ... | ... |
| 35 | 1.69$^{+0.26}_{-0.26}$ | 6.00 | 0.996 | 4.81 | 0.60 | 1.69$^{+0.16}_{-0.27}$ | 6.00 | 0.996 | 0.02$^{+0.03}_{-0.01}$ | 6.67 | 0.004 |

Notes. In addition to the most likely redshift, we report the two most likely redshifts for each galaxy when available, along with the redshift ranges for each peak and the fractions of $P(z)$ contained in those peaks. 

a ID numbers from Coe et al. (2006).
b Bayesian photometric redshift (BPZ) and uncertainty from 95% confidence interval.
c Template SEDs used in the BPZ code as described in Section 4.1.1, where 1 = El_cw, 2 = Scd_cw, 3 = Sbc_cw, 4 = Im_cw, 5 = SB3_kin, 6 = SB2_kin, 7 = 25 Myr, and 8 = 5 Myr. Non-integer values are for templates interpolated between adjacent templates.
d Integrated $P(z)$ contained within 0.11 $(z_b + \Delta z_b)$.
e Chi square quality of photo-z fit.
f Modified reduced chi-square fit, where the templates are given uncertainties.
g Redshift ranges for the two most likely peaks.
h Integrated $P(z)$ contained within the local minima of $P(z)$ for each peak.

(Tabulation is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
4.1.2. Photometric Redshift Measurement Uncertainties

It is important to understand the origins of photo-$z$ uncertainties in order to have confidence in their values. There are two types of uncertainties in photo-$z$'s: (1) photometric measurement uncertainties and (2) template-mismatch variance (Lanzetta et al. 1998; Fernández-Soto et al. 2001, 2002; Chen et al. 2003). Photometric measurement uncertainties are well understood, and they are responsible for the width of $P(z)$, which determines the reported photo-$z$ uncertainties. Faint galaxies with larger photometric measurement uncertainties will yield larger uncertainties in the photo-$z$'s than brighter galaxies. If the photometric measurement uncertainties are very large, then the photo-$z$ will be poorly constrained, because this results in multiple peaks in $P(z)$ corresponding to many possible redshifts. The other possible uncertainty comes from template mismatches, which is a systematic error due to the finite number of templates used in the photo-$z$ determination. Not all galaxies will be well represented by our template SEDs, yielding large $\chi^2$ values.

One method to decrease template-mismatch errors is to introduce more template SEDs, since that increases the chance that there exist good matching SED templates for each galaxy. While this can improve low-redshift performance, it also increases the number of degenerate solutions and therefore gives poorer high-redshift performance (Hildebrandt et al. 2008). Degenerate photo-$z$'s occur when different SED templates fit the photometry equally well, resulting in multiple peaks in $P(z)$ and therefore multiple possible redshifts. We consider galaxy redshifts degenerate if they have two or more peaks in $P(z)$ at 95% confidence separated by $\Delta z > 1$. In these cases, the resultant reported uncertainties are very large and the galaxy redshift is poorly constrained. We are mainly interested in good performance at high redshift and therefore do not increase the number of SED templates.

Template mismatches are also the cause for “catastrophic” photo-$z$ errors that occur, where the photo-$z$ is incorrect and the uncertainty does not include the correct redshift (Ellis 1997; Fernández-Soto et al. 1999; Benítez 2000). Catastrophic photo-$z$ errors typically occur because multiple peaks in $P(z)$ are incorrectly suppressed, leaving only one peak. The suppression of multiple peaks in bright galaxies likely occur because of their small photometric uncertainties yielding large $\chi^2$ values without taking into account the systematic uncertainties in the SED templates, which exaggerate the differences between the different SED template fits that correspond to different peaks in $P(z)$. This suppresses the peaks at other redshifts, resulting in possible “catastrophic” photo-$z$ errors (D. Coe 2009, private communication).

It is likely that the incorrect suppression of peaks in $P(z)$ can be fixed through the introduction of SED uncertainties in the initial $\chi^2$ fit, although such an addition requires an understanding of those uncertainties using large surveys with both photo-$z$ and spec-$z$'s. This is neither in the scope of the UDF nor this paper, and is being investigated elsewhere (D. Coe et al. 2009, in preparation). In the mean time, the best we can do is reject photo-$z$'s based on their $\chi^2_{\text{mod}}$ values. However, $\chi^2_{\text{mod}}$ is not a true statistical test like $\chi^2_{\nu}$, and therefore crits normally appropriate for $\chi^2_{\nu}$ are not valid for $\chi^2_{\text{mod}}$. Additionally, galaxies with $J$- and $H$-bands data have median $\chi^2_{\text{mod}}$ larger by $\sim 0.7$ than those without infrared (IR) data, although the inclusion of the IR data improves the reliability of the photo-$z$'s because of the significantly increased lever arm (Coe et al. 2006). We therefore don’t use the same cut as used in Coe et al. (2006) ($\chi^2_{\text{mod}} < 1$), but rather use $\chi^2_{\text{mod}}$ to conservatively remove possible bad photo-$z$ fits. While we do present all the photo-$z$ fits, we only include those with $\chi^2_{\text{mod}} < 4$ for our $z \sim 3$ galaxy sample. This cut only reduces the total number of galaxies with photo-$z$'s by $\sim 5\%$ (to 1385 galaxies).

4.1.3. Comparison of Photometric and Spectroscopic Redshifts

In order to test the accuracy of the photo-$z$'s, we compare the redshifts with spectroscopic redshifts (spec-$z$'s). We compile a list of 100 reliable spec-$z$'s in the UDF that match our sample from Section 3.5 (see Table 3). In this sample, 18 spec-$z$’s are from the VIMOS VLT Deep Survey (VVDS; Fèvre et al. 2004), where we only include redshifts with 95% confidence and multiple lines. Another 22 redshifts come from the GOODS VLT VIMOS survey (VIMOS; Poppeso et al. 2009), where we include redshifts with A or B quality spectra. These spectra have good cross-correlation coefficients of the spectra with the templates and multiple lines are well identified. An additional 6 redshifts are from Szokoly et al. (2004) using the VLT FORS1/FORS2 spectrographs, where we use only those flagged as “reliable” redshifts (quality flags “2” or “24”). The remaining 57 redshifts are from the GOODS VLT FORS2 survey (FORS2: Vanzella et al. 2005, 2006, 2008, 2009), where we only include redshifts from A or B quality spectra. We do not include redshifts from the slitless spectra obtained as part of the Grism ACS Program for Extragalactic Science (GRAPE; Pirzkal et al. 2004), since the redshift determinations do not provide an independent check to photo-$z$’s because photo-$z$’s were used to help identify the emission lines (Xu et al. 2007).

The photo-$z$’s agree relatively well with the spec-$z$’s (see left panel of Figure 5), and have 100% agreement in the redshift interval of interest ($2.5 \lesssim z \lesssim 3.5$), although only five objects have spec-$z$’s at these redshifts. There are clearly some galaxies that have incorrect photo-$z$’s at lower redshift where the $u$-band does not sample the Lyman break. Of the 100 galaxies from Table 3, 97 have $\chi^2_{\text{mod}} < 4$, of which 93 have $\chi^2_{\text{mod}} < 0.99$. The galaxy at a spec-$z$ of 1.99 (ID 6834) has a $\chi^2_{\text{mod}} \sim 17$ and the resultant photo-$z$ should be ignored.

Only object 8585 meets our criteria, but has a significantly different photo-$z$ than its spec-$z$ and does not include the correct redshift in its $P(z)$. This object, with a spec-$z$ of $z = 0.3775$ (Fèvre et al. 2004) and a photo-$z$ of $1.45 \pm 0.24$, is a case where the spec-$z$ may be wrong. In general we tried to minimize this possibility by selecting reliable spec-$z$'s, but the spec-$z$’s can still be wrong as seen in some comparisons of Fernández-Soto et al. (2001). In our case, the photometric redshift yields a good fit to the SED templates, and the fit to the SED template at the spec-$z$ is a bad fit. The published spectrum shows that the spec-$z$ is mainly determined by the $H\alpha$ line. This could easily be confused with the OII line for a galaxy with a redshift of $z = 1.43$, which would be consistent with our photo-$z$. This leaves one galaxy with a possible “catastrophic error,” although it is not in the redshift interval of interest ($2.5 \lesssim z \lesssim 3.5$).

4.1.4. Improvement of Photo-$z$’s with the Addition of a $u$ band

A comparison of the redshift interval ($2.5 \lesssim z \lesssim 3.5$) in the two panels of Figure 5 shows a significant improvement in the photo-$z$’s with $u$-band data. The left panel depicts photo-$z$’s

9 Most of these redshifts are based on observations made with ESO Telescopes at the La Silla or Paranal Observatories under program ID(s) 66.A--0270(A), 67.A--0418(A),171.A--3045, 170.A--0788, 074.A--0709, and 275.A--0560.
with u-band data while the right panel depicts photo-z’s without u-band data. The u band helps prevent catastrophic redshift errors that can occur because of a similarity in the colors of low-redshift galaxies and high-redshift galaxies (Ellis 1997; Fernández-Soto et al. 1999; Benítez 2000). Usually, this degeneracy causes \( P(z) \) to have multiple peaks representing both possible redshifts in the absence of u-band data (Coe et al. 2006). As discussed in Section 4.1.2, however, sometimes secondary peaks are absent yielding incorrect redshift uncertainties and possibly incorrect redshifts. For example, three galaxies (IDs 830, 4267, 5491) with \( \chi^2_{mod} < 4 \) and ODDS > 0.99 have catastrophic redshift errors without u-band photometry and gain accurate photo-z’s based on their spec-z’s after we include the u band (e.g., see Figure 6). As expected, the u data clearly improve the photo-z’s of galaxies at \( z \sim 3 \) when compared to the spec-z’s. However, we are constrained to discussing small number statistics, and the true contamination fraction is unknown.

We would ideally like to compare a larger number of \( z \sim 3 \) photo-z’s to spec-z’s to get a better understanding of the improvement of the photo-z’s with the addition of the u band, although such spectroscopic data are lacking in the UDF. However, since the u-band samples the Lyman break of \( z \sim 3 \) galaxies, and we know that the photo-z’s with u band are more reliable than those without, we can investigate the changes in the photo-z’s. We therefore compare all the photo-z’s with \( \chi^2_{mod} < 4 \) of galaxies with and without the u-band data in Figure 7, which highlights two effects. The first is that \( P(z) \) changes markedly for 125 galaxies, mostly in the redshift interval \( 2 \lesssim z \lesssim 3 \), where the u band probes the Lyman break. Of these, 102 change their photo-z’s from \( z \sim 1 \) to \( z \sim 2 \), whereas 23 switch in

![Figure 5](image-url)

**Figure 5.** Differences in spectroscopic redshifts (spec-z) and photometric redshifts (photo-z) compared to the 100 spec-z described in Section 4.1.3, where the photo-z uncertainties are for a 95% confidence interval. The left panel plots the difference in spec-z and photo-z with u band, and the right panel plots the same but for the photo-z without the u band. The quality of the photometric redshift fit is described by the \( \chi^2_{mod} \) (see Section 4.1.1), where objects with good fits, \( \chi^2_{mod} < 4 \), are marked with triangles, and objects with \( \chi^2_{mod} > 4 \) are marked with open crosses. There is one point in the left panel at \( z \sim 2 \) that has a large \( \chi^2_{mod} \) (~17) and should be ignored as it is not a good fit to any SED templates with the u band.

**Table 3**

Catalog of Galaxies with Reliable Spectroscopic Redshifts in the UDF

| ID\(^a\) | Survey | \( z_{spec} \) | \( z_u \)\(^b\) | \( \chi^2_{mod} \)\(^c\) | ODDS\(^d\) | \( V \) (mag) | \( u - V \) (mag) | \( u - B \) (mag) | \( V - z' \) (mag) |
|---|---|---|---|---|---|---|---|---|---|
| 3088 | FORS2 | 0.13 | 0.06 | 1.91 | 1.00 | 22.85 | 1.99 | 0.11 | 0.48 |
| 5670 | VVDS | 0.13 | 0.09 | 0.03 | 1.00 | 21.23 | 2.00 | 1.12 | 0.54 |
| 1971 | VVDS | 0.15 | 0.02 | 0.07 | 1.00 | 20.46 | 1.48 | 0.82 | 0.37 |
| 2974 | VIMOS | 0.15 | 0.15 | 1.51 | 1.00 | 24.08 | 1.97 | 0.99 | 0.49 |
| 5620 | VVDS | 0.21 | 0.21 | 0.75 | 1.00 | 23.42 | 0.88 | 0.43 | 0.01 |
| 3822 | VIMOS | 0.21 | 0.18 | 0.59 | 1.00 | 19.14 | 1.91 | 0.87 | 0.70 |
| 1000 | FORS2 | 0.21 | 0.21 | 1.08 | 0.97 | 23.39 | 0.93 | 0.46 | 0.01 |
| 5606 | VVDS | 0.23 | 0.16 | 0.05 | 1.00 | 21.14 | 1.79 | 0.82 | 0.55 |
| 5491 | VIMOS | 0.23 | 0.17 | 1.94 | 1.00 | 22.24 | 0.64 | 0.30 | 0.15 |
| 7847 | VVDS | 0.33 | 0.31 | 0.02 | 1.00 | 22.00 | 2.97 | 1.36 | 1.10 |

Notes. Redshift surveys are VVDS (Fèvre et al. 2004), VIMOS (Popesso et al. 2009), Szokoly et al. (2004), and FORS2 (Vanzella et al. 2005, 2006, 2008, 2009). V magnitudes are total AB magnitudes, and colors are isophotal colors. All photometry other than the u-band are from Coe et al. (2006). Nondetections in u-band are given 3\( \sigma \) limiting magnitudes.

\(^a\) ID numbers from Coe et al. (2006).

\(^b\) Bayesian Photometric Redshift (BPZ) and uncertainty from 95% confidence interval.

\(^c\) Modified reduced chi square fit, where the templates are given uncertainties.

\(^d\) Integrated \( P(z) \) contained within 0.1\((1+z_0)\).

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
Figure 6. Object 830: an example of a galaxy with $z_{\text{spec}} = 2.44$ (Popesso et al. 2009) that has a catastrophic redshift error before the addition of the $u$ band. The left-hand side figures show the photo-$z$ fit without $u$ band with $z = 0.24 \pm 0.15$ and the right-hand side figures show the fit with $u$ band with $z = 2.72 \pm 0.37$. The rectangles represent the assumed uncertainty of the SED template used for $\chi^2_{\text{mod}}$. Blue points are the $u$-band data, green are the ACS data, and red are the NICMOS data. Filled circles are for detected and observed data points, and squares are for unobserved data points. The addition of the $u$ band rules out the possibility of this being a low-redshift galaxy, and corrects the catastrophic redshift. (A color version of this figure is available in the online journal.)

the other direction. This change is a result of the code selecting different $P(z)$ peaks as the most probable redshift for galaxies having multiple peaks.

The second effect shown in Figure 7 is the removal of the degeneracy of $z \sim 3$ and $z \sim 0.2$ photo-$z$’s, due to the removal of one of the peaks in $P(z)$. One hundred seventy five galaxies went from being degenerate to non-degenerate, and are marked by the red crosses in Figure 7. Not all of the degenerate photo-$z$’s are removed; however, 51 galaxies are degenerate between these redshifts as marked by the blue crosses in Figure 7, of which 17 were not degenerate before the addition of the $u$ band. The new degeneracies occur when the $u$-band best-fit redshift is different compared to the best fit to the other bands. The old degeneracies that are not removed occur when the $u$ band does not conclusively rule out another template, often because they are faint. Figure 7 also includes galaxies with $\chi^2_{\text{mod}} < 4$ in the photometric redshift fits selected to be at $z \sim 3$ using the color selection method described in Section 4.2 (below), which is useful when comparing the two methods. Figure 8 shows an example of both effects, where the $u$-band changes the photo-$z$ and removes a secondary peak in $P(z)$ for a high-redshift galaxy.

Out of 1384 galaxies with $\chi^2_{\text{mod}} < 4$, there are 274 galaxies that have photo-$z$’s in the interval $2.5 \leq z \leq 3.5$ without $u$ band. The addition of the $u$ band increases this number by 91 to 365 galaxies that have a photo-$z$ in this redshift interval either with or without the $u$ band (including the 23 that switched to low redshift). Of these 365 galaxies, 161 galaxies either had their photo-$z$ changed or the degeneracy removed with the addition of the $u$ band. This shows that the addition of the $u$ band significantly changed the photo-$z$’s of the $z \sim 3$ galaxy sample by $\sim 50\%$.

4.2. Color Selection

Color selection is an efficient means to select high-redshift galaxies, and extensive research has been carried out to determine the best color criteria to minimize the interloper fraction from low-redshift galaxies or stars (e.g., Steidel et al. 1996a, 1996b, 1999, 2003; Adelberger et al. 2004; Cooke et al. 2005). The color selection criteria used in these studies are based on predicted colors of model star-forming galaxies at high redshift, which are then confirmed with $z_{\text{spec}}$’s, that result in known contamination fractions between 3%-5% (Steidel et al.
selected in a \((u - V)\) versus \((V - z')\) color–color plane. Figure 9 plots the expected colors of different model galaxies at different redshifts in the \((u - V)\) versus \((V - z')\) diagram.

The region defining candidate \(z \sim 3\) LBGs is indicated with the dashed black line in Figure 9. In order to avoid selecting low-redshift galaxies, this selection region excludes SED template colors for \(z \lessapprox 2.5\). The deviations from SED templates and photometric errors will cause intrinsic scatter in the color–color plane. We therefore leave \(\sim 0.2\) mag between our color selection and the low-redshift elliptical galaxy SEDs that cause the largest contamination for galaxies at \(z \sim 3\). In addition to the cut in the \((u - V)\) versus \((V - z')\) diagram, we also apply secondary color cuts using the \((u - B)\) color to improve our color selections by removing potential interlopers. We also include a cut on \(V\)-band magnitude, where the bright end does not remove any LBG candidates and the faint end is the \(V\)-band magnitude determined in Section 3.5 to keep the S/N of the \(u\) band > 3σ. The following conservative constraints are used to select LBG candidates:

\[
\begin{align*}
(u - V) & \geq 1.0, \\
(u - B) & \geq 0.8, \\
(V - z') & \leq 0.6, \\
3(V - z') & \leq (u - V) - 1.2, \\
23.5 & \leq V \leq 27.6.
\end{align*}
\]

4.2.2. Reliability of Color Selection

In order to test our selection criteria, we compare our selection of the 100 galaxies with reliable spec-z’s as described in Section 4.1.3 and Table 3. These spectra allow us to test the efficacy of selecting targets via the \((u - V)\) versus \((V - z')\) color plane (Figure 10). No \(z < 2.5\) galaxies with reliable spec-z’s passed our color cut confirming that our cut effectively excludes low-redshift galaxies. We note that there are three \(z > 2.5\) objects that do not meet our color criteria in Figure 10. The \(z = 3.68\) object (triangle, object 865) is classified as a quasar by Szokoly et al. (2004) due to active galactic nuclei (AGNs) activity. The \(z = 4.77\) object with \((V - z')\) is a bright \(V\)-band dropout galaxy, whose \(V\)-band magnitude (27.26) is just bright enough to remain in the sample before the color cuts. Finally, the \(z = 3.80\) is also excluded by our color cut due to a decrease in the \(V\)-band magnitude, reddening the color.

There are a number of objects that could contaminate our sample of \(z \sim 3\) LBGs because their spectra are unusual and thus do not match our model SEDs. While at brighter magnitudes the color selection criteria include stars and AGNs, for our \(V > 23.5\) sample the color selection criteria are mainly contaminated by low-redshift galaxies at \(z \lessapprox 0.2\) (Reddy et al. 2008). Additionally, about 1/3 of the Distant Red Galaxies (DRGs) fall within the color selection sample of Steidel (van Dokkum et al. 2006), which is similar to our criteria. DRGs are galaxies at \(z \gtrsim 2\) that have faint UV luminosities, have previously undergone their episode(s) of star formation (Franx et al. 2003), and have stellar masses \(\gtrsim 10^{11}M_{\odot}\) (van Dokkum et al. 2004, 2006). However, given the DRGs’ estimated space density of \((2.2 \pm 0.6) \times 10^{-4}\) Mpc\(^{-3}\) (van Dokkum et al. 2006), Reddy & Steidel (2009) conservatively determine that the fractional contribution would be \(\sim 2\%) for UV-faint sources such as our sample.

---

**Figure 7.** Photo-z’s without \(u\)-band data vs. Photo-z’s with \(u\)-band data for objects with \(\chi_{\text{phot}}^2 < 4\) in both cases. The red crosses designate galaxies where the photo-z’s are degenerate without \(u\) band, and the blue crosses are for degenerate photo-z’s with \(u\) band. The degeneracy in redshift occurs when galaxies have at least two significant peaks in the \(P(z)\), usually due to the degeneracy in the colors of a low-redshift galaxies and high-redshift galaxies. The orange dots are those objects that are selected using the color selection technique in Section 4.2. We note although the photo-z’s with \(u\) band may be incorrect, the addition of the \(u\) band made a large difference in the photo-z’s of \(z \sim 3\) galaxies.

2003; Reddy et al. 2008). Such low contamination fractions are achieved by avoiding colors where low-redshift galaxies reside. While color selection techniques do not provide a complete sample of LBGs, they do an excellent job of selecting galaxies in a specific redshift range, as evidenced by their contamination fractions. While the UDF data provide an extraordinary data set, they also use a different set of filters than used in previous color selection studies, meaning we must define new color criteria for LBG selection. We therefore develop and calibrate new color selection studies, meaning we must define new color criteria for LBG candidates at \(z \sim 3\) galaxies.

4.2.1. Color Selection Criteria

Using the same approach as Steidel et al. (1996a, 1996b, 1999, 2003), Adelberger et al. (2004), and Cooke et al. (2005), we derive galaxy colors by evolving different galaxy SED templates to high redshift convolved with the total throughput of the different filters shown in Figure 2. We include galaxy SED templates consistent with our photometric redshifts described in Section 4.1, with galaxy SED templates from Kinney et al. (1996), Coleman et al. (1980), and Bruzual & Charlot (2003). In addition, we use a 2.0 Gyr Elliptical Galaxy from the Bruzual & Charlot (2003) synthesis code (E2G) since it is quite different than the elliptical galaxy SED template from Coleman et al. (1980) and represents possible low-redshift galaxies we wish to avoid. We apply the \(K\)-correction for different redshifts and correct for the opacity from the intergalactic medium by using estimates from Maddox (1995). The resultant colors and redshifts of the SED templates are used to determine the appropriate color criteria to maximize the number of LBG candidates at \(z \sim 3\) while minimizing the contamination from objects at other redshifts. We test multiple color–color planes and find that for our set of filters, \(z \sim 3\) LBGs can best be
As discussed earlier, to get a sense of the number of possible interlopers, we would like to have a large number of spectra to determine the contamination fraction. However, we only have a relatively small number of spectra (100) as shown in Figure 10 and Table 3. Instead, we compare our color cuts to the \((U - G)\) versus \((G - R)\) color cuts of Steidel et al. (2003) for redshifts \(2.7 \leq z \leq 3.4\), and assume that our sample has similar contamination. In Figure 9, we determine the redshift that corresponds to Steidel’s color cut for a given SED template in \((U - G)\) and \((G - R)\). We then determine the \((u - V)\) and \((V - z')\) colors that this SED template has at this redshift and compare those resulting colors to our color criteria by marking them with filled black circles in Figure 9. The filled black circles are outside or near the edge of our color selection criteria, which shows that we are more conservative in our cut for the redder SED templates and about equivalently conservative for the bluer ones as the cut in Steidel et al. (2003). We therefore infer that our contamination fraction is comparable to that of Steidel et al. (2003) and Reddy et al. (2008), where the contamination fraction of \(z \sim 3\) LBGs is \(\sim 3\%\) for objects \(23.5 \leq V \leq 25.5\) mag.

5. SAMPLE OF \(z \sim 3\) GALAXIES

Photometric redshifts and color selection are both good ways to select \(z \sim 3\) galaxies. Photometric redshifts have the advantage of creating a larger sample since they can measure redshifts in regions of color space that color-selected samples avoid because of low-redshift galaxies. They also use more information than color selection, including all colors simultaneously to constrain the redshift. However, while the error rate of the photometric redshifts is not well defined, color selection is efficient, has a clearly defined contamination fraction, and allows direct comparisons to other studies. The completeness of our LBG selection is limited primarily on the \(u\)-band depth because the ACS bands from \(HST\) are deeper. In order to characterize this completeness, we compare our color-selected LBGs with other studies in Section 5.3. To justify such comparisons, we compare the redshift distribution of this sample in Section 5.1, and investigate our uncertainties from cosmic variance in Section 5.2.

In choosing our color selection criteria we chose to be conservative and create a less complete catalog with a small contamination fraction similar to that of Steidel et al. (2003) and
squares for \( z > 2.5 \), the dashed lines are \( z < 2.5 \), and the symbols represent redshifts of 2.5, 2.8, 3.0, and 3.2 which increase with increasing \((u-V)\) color. We include galaxy SED templates from Kinney et al. (1996) for starbursting galaxies with different reddening (SB2, SB3), from Coleman et al. (1980) for star-forming galaxies (Im), spiral galaxies (Scd, Sbc), and elliptical galaxies (El). In addition, we use two faint blue galaxy SEDs with ages of 25 and 5 Myr and metallicities of Z = 0.08 (25 Myr, 5 Myr), and a 2.0 Gyr Elliptical Galaxy (E2G) from the Bruzual & Charlot (2003) synthesis code. The area above and to the left of the dashed black line is 2.0 Gyr Elliptical Galaxy (E2G) from the Bruzual & Charlot (2003) synthesis code. The area above and to the left of the dashed black line is.

**Figure 9.** \((u-V)\) vs. \((V-z')\) color–color diagram depicting different model galaxies at different redshifts, where the solid lines are \( z > 2.5 \), the dashed lines are \( z < 2.5 \), and the symbols represent redshifts of 2.5, 2.8, 3.0, and 3.2 which increase with increasing \((u-V)\) color. We include galaxy SED templates from Kinney et al. (1996) for starbursting galaxies with different reddening (SB2, SB3), from Coleman et al. (1980) for star-forming galaxies (Im), spiral galaxies (Scd, Sbc), and elliptical galaxies (El). In addition, we use two faint blue galaxy SEDs with ages of 25 and 5 Myr and metallicities of Z = 0.08 (25 Myr, 5 Myr), and a 2.0 Gyr Elliptical Galaxy (E2G) from the Bruzual & Charlot (2003) synthesis code. The area above and to the left of the dashed black line is.

**Figure 10.** Comparison of our selection criteria to 100 reliable spec–z galaxies as described in Section 4.1.3. Object redshifts are binned and represented with different symbols, where crosses are for objects with \( z < 2.0 \), diamonds for \( 2.0 < z < 2.5 \), open circles for \( 2.5 < z < 3.0 \), triangles for \( 3.0 < z < 3.5 \), and squares for \( z > 3.5 \). The dashed line depicts our color cut.

Reddy et al. (2008) of 3%. Depending on the purpose, a higher contamination fraction is acceptable in exchange for a larger and more complete sample. The photo–z sample yields a more complete sample, and may even have a similar contamination fraction based on our spectroscopic sample, although due to our small numbers at the redshift of interest, it is not clear at this point. If the lowest contamination fraction possible is needed, a subset of \( z \sim 3 \) LBGs that are both color selected and photo–z selected are the most robust candidates available.

We present both samples of \( z \sim 3 \) LBGs in Table 4, for a total of 407 candidates, along with their photo–z’s and colors. We distinguish the samples by designating them as either color selected, photo–z selected, or both. The photo–z sample consists of galaxies in the redshift interval \( 2.5 \leq z \leq 3.5 \) that have \( \chi^2_{\text{mod}} < 4 \), and \( \chi^2_{\text{mod}} < 4 \), and contains 365 galaxies. Of the 42 galaxies not included in our photo–z sample, two have \( z \sim 2.2 \), 11 have \( z > 3.5 \), eight others have \( \chi^2_{\text{mod}} < 0.99 \), and 21 others have \( \chi^2_{\text{mod}} > 4 \). The color-selected sample contains 260 galaxies, all of which have photo–z’s with \( z > 2 \), and 258 that have \( z > 2.5 \) and 11 that have \( z > 3.5 \). However, the overlap of the two samples is only 216 galaxies. We show the final LBG selection in Figure 11, which plots all objects from Table 1 on a color–color diagram, with 287 galaxies falling in the color selection region corresponding to constraints 4, 6, and 7 from Section 4.2.1. There are 27 galaxies that are both color selected and photo–z selected are marked by red circles, the 42 galaxies that are only color selected are marked by green squares, and the 147 galaxies selected only by photo–z’s are marked by blue stars, yielding a total of 407 \( z \sim 3 \) LBG candidates.

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

**Figure 11.** All objects from Table 1 on a color–color diagram, where the dashed line refers to the selection criteria for constraints 4, 6, and 7 from Section 4.2.1. There are 27 objects that are in the color selection area in this diagram but are not color selected because of constraint 5 from Section 4.2.1. The 218 galaxies that are both color selected and photo–z selected are marked by red circles, the 42 galaxies that are only color selected are marked by green squares, and the 147 galaxies selected only by photo–z’s are marked by blue stars, yielding a total of 407 \( z \sim 3 \) LBG candidates.

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

### 5.1. Redshift Distribution

In order to understand the redshift distribution of the color-selected LBG sample, we look at the photo–z’s that meet the color selection criteria and our photo–z criteria of \( \chi^2_{\text{mod}} < 4 \). This leaves a sample of 235 galaxies that have a mean redshift of \( 3.0 \pm 0.3 \) in the redshift interval \( 2.4 \leq z \leq 3.8 \) (see left panel in Figure 12), with a median uncertainty in the photo–z’s of \( \pm 0.4 \). Additionally, we investigate the redshift distribution by adding the probability histograms \( P(z) \) of the individual galaxies, which yields a similar result (see the right panel in Figure 12). The redshifts selected are similar to those of Steidel et al. (2003), with \( \sim 80\% \) of our sample matching their reported redshift interval \( 2.7 < z < 3.4 \). In fact, their distribution is very similar to ours, with a number of their LBGs falling outside of this interval. Given the large uncertainties in our photo–z’s, we conclude that our color-selected redshift distribution is similar to that of Steidel et al. (2003) within our uncertainties. The similar
redshift distribution of our color-selected sample justifies our comparison of the number densities of LBGs in Section 5.3.

5.2. Cosmic Variance

The UDF has a very small volume, with our overlap area consisting of 11.56 arcmin², which in the redshift interval 2.5 ≤ z ≤ 3.5 is a comoving volume of ~38,000 Mpc³. A single pointing with a small solid angle and such a small volume is likely to be affected by cosmic variance, yielding larger than Poisson uncertainties in the LBG number counts. It is important to estimate the cosmic variance effect in order to understand the systematic uncertainties for comparisons with number densities of LBGs in the literature.

We calculate the cosmic variance using the code from Newman & Davis (2002) and the prescription from Adelberger et al. (2005) to get the fractional error per count σ/N for our given volume in the redshift interval 2.5 ≲ z ≲ 3.5. The variance is determined from the integral of the linear regime of the cold dark matter (CDM) power spectrum (P(k)),

$$\sigma^2_{\text{CDM}} = \frac{1}{8\pi^3} \int P(k) \hat{W}(k)^2 d^3 k,$$

where \( \hat{W}(k) \) is the Fourier transform of our survey volume. Since we want the variance of galaxy counts rather than CDM fluctuations, we need to correct for the clustering bias (b) of LBGs to get their variance (\( \sigma^2_g \)), where \( \sigma^2_g \approx b^2 \sigma^2_{\text{CDM}} \). The galaxy bias for typical LBGs is then calculated from the ratio of galaxy to CDM fluctuations in spheres of comoving radius 8 h⁻¹ Mpc, where \( \sigma_b(z) \) represents the CDM fluctuations for our redshift, and \( b = \sigma_{g,\text{LGB}}/\sigma_b(z) \) (Adelberger et al. 2005). The resulting variance depends on a fit to the LBG correlation function \( \xi_g(r) = (r/r_0)^{-\gamma} \), where \( r_0 \) is the spatial correlation length and \( \gamma \) the correlation index. The galaxy variance is then

$$\sigma^2_{g,\text{LGB}} = \frac{72r_0/8 \, h^{-1}\mathrm{Mpc} \gamma^0}{(3 - \gamma)(4 - \gamma)(6 - \gamma)2^\gamma},$$

(Peebles 1980, Equation (59.3)) from which we can then calculate the fractional error per LBG count.

Empirical fits to the correlation function yield differing values for \( r_0 \) and \( \gamma \) depending on the sample, redshift distribution, luminosity range, and redshift, which in turn affect the value of \( \sigma^2_g \) and our fractional uncertainty (Adelberger et al. 2005; Hildebrandt et al. 2007, 2009; Kashikawa et al. 2006; Lee et al. 2006; Ouchi et al. 2004, 2005; Yoshida et al. 2008). We avoid looking at samples covering a small area of the sky such as the HDF (Giavalisco & Dickinson 2001), as such studies are also plagued by cosmic variance as shown in Ouchi et al. (2005). The values in the larger studies generally vary between \( r_0 \sim 2.8 \sim 5.5 \) and \( \gamma \sim 1.5 \sim 2.2 \), with an increasing \( r_0 \) and \( \gamma \) with increasing luminosity, i.e., the brighter LBGs are more strongly clustered.

There is also some minor evolution with redshift, where the higher redshift galaxies are more clustered (Hildebrandt et al. 2009). These values result in \( \sigma^2_{g,\text{LGB}} \sim 0.56 \sim 1.1 \) which correspond to a fractional error per count of \( \sim 0.14 \sim 0.28 \). Our sample includes the fainter less clustered LBGs at \( z \sim 3 \), so we are on the less clustered side of this range. We therefore adopt a fractional error per count (\( \sigma/N \)) of \( \sim 0.2 \) in the rest of this study, which suggests that we could detect a relatively large over-density or under-density in our small volume. In fact, there is evidence of an over-density of \( z \sim 3.7 \) galaxies in the Chandra Deep Field South, of which the UDF is a part (Kang & Im 2009). However, no clear over-density is indicated in the correlation length measured from the GOODS survey covering the same area on the sky (Lee et al. 2006) at slightly higher redshift. We use the above estimate of the cosmic variance for our small field of view to constrain our results of the number densities of LBGs in Section 5.3.

5.3. LBG Number Counts

The number counts of \( z \sim 3 \) LBGs per unit of magnitude indicate the completeness of the LBG selection, and can be compared to number counts from other studies. Such data are only

| ID | \( z_b \) | \( \chi^2_{mod} \) | 0DDS | Type | V (mag) | \( u - V \) (mag) | \( u - B \) (mag) | \( V - z' \) (mag) |
|----|--------|-------------|------|------|---------|----------------|----------------|----------------|
| 22 | 3.23 + 0.14 | 0.44 | 1.00 | 2 | 27.38 ± 0.03 | 1.53 ± 0.36 | 0.96 ± 0.36 | 0.49 ± 0.04 |
| 76 | 2.62 + 0.10 | 0.52 | 1.00 | 2 | 26.47 ± 0.02 | 1.39 ± 0.16 | 1.19 ± 0.16 | 0.11 ± 0.03 |
| 84 | 3.11 + 0.40 | 0.01 | 1.00 | 1 | 26.56 ± 0.02 | 2.40 ± 0.35 | 1.69 ± 0.35 | 0.03 ± 0.04 |
| 97 | 2.87 + 0.30 | 0.13 | 1.00 | 1 | 25.02 ± 0.01 | 2.01 ± 0.06 | 1.48 ± 0.07 | 0.08 ± 0.01 |
| 99 | 2.81 + 0.37 | 0.32 | 1.00 | 2 | 24.74 ± 0.01 | 1.96 ± 0.07 | 1.51 ± 0.08 | 0.52 ± 0.01 |
| 101 | 2.66 + 0.36 | 0.17 | 1.00 | 2 | 27.38 ± 0.02 | 1.45 ± 0.32 | 1.09 ± 0.32 | 0.09 ± 0.05 |
| 131 | 3.06 + 0.40 | 0.21 | 1.00 | 1 | 26.95 ± 0.02 | 2.02 ± 0.35 | 1.43 ± 0.36 | 0.03 ± 0.05 |
| 209 | 2.67 + 0.30 | 0.93 | 1.00 | 3 | 26.92 ± 0.02 | 1.27 ± 0.34 | 1.26 ± 0.34 | -0.31 ± 0.05 |
| 213 | 3.14 + 0.41 | 0.18 | 1.00 | 2 | 26.91 ± 0.02 | 1.95 ± 0.34 | 1.19 ± 0.35 | 0.56 ± 0.04 |
| 230 | 3.70 + 0.46 | 0.00 | 1.00 | 3 | 25.68 ± 0.01 | 3.08 ± 0.35 | 1.29 ± 0.36 | 0.44 ± 0.02 |

Notes. Photometric redshifts should only be used if they have low \( \chi^2_{mod} \) and good 0DDS values as described in Section 4.1.1. V magnitudes are total AB magnitudes, and colors are isophotal colors. All photometry other than the \( u \) band are from Coe et al. (2006). Non-detections in \( u \) are given 3σ limiting magnitudes.

a ID numbers from Coe et al. (2006).

b Bayesian photometric redshift (BPZ) and uncertainty from 95% confidence interval.

c Modified reduced chi-square fit, where the templates are given uncertainties.

d Integrated \( P(z) \) contained within 0.1(1+z_b).

e Type of LBG selection, where 1=both color and photo-z selected, 2=only photo-z selected, and 3=only color selected.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
available for color-selected samples, and we therefore only use our color-selected sample in our comparison. The same comparison could be accomplished with the luminosity function, which we do not calculate because we only have one pointing and our comoving volume is small. In other words, we have a small number of LBGs that in conjunction with the uncertainty due to cosmic variance discussed above, would not yield meaningful constraints on the luminosity function. Additionally, to calculate the luminosity function, Monte Carlo simulations need to be run as described in Reddy et al. (2008) that are computationally prohibitive given our complex analysis technique to get reliable photometry with largely varying PSFs (Laidler et al. 2007). We therefore compare our results with the number counts from other studies. We stress that we are comparing number counts that are not corrected for completeness, and therefore the counts will fall at faint magnitudes in each study due to sample incompleteness.

Our ground-based LRIS images have much greater PSF FWHMs ($\sim 1''$) than the HST V-band image ($\sim 0''.09$), thus affecting the observed number counts. The dominant effect is caused by the blending of neighboring objects that affects the color of objects and therefore their selection. In addition, at significantly lower resolution, isolated compact faint objects have part of their flux lost to the noise floor of the background. This causes the faintest objects to go undetected in the low-resolution images, even if they would have been detected in a similarly sensitive high-resolution image. We use the HST V-band image to determine our high-resolution-detection (HRD) number counts and correct for this resolution effect. We convolve the HST V-band image with the PSF modeled from the LRIS V-band image (FWHM of $\sim 1''$) that was taken concurrently with the $u$-band data. This yields a low-resolution-detection (LRD) image from which a segmentation map is generated using SExtractor.

The final photometry is measured with this new segmentation map in all bands using sexseg as discussed in Section 3.4, and then the same color selection is used as discussed in Section 4.2.1. Figure 13 shows the number counts per half-magnitude bin per square arcminute for both the HRD and LRD, along with number counts from Reddy et al. (2008), the Keck Deep Field (KDF; Sawicki & Thompson 2006), and Steidel et al. (1999). For the HRD sample, we include only Poisson uncertainties, while for the LRD we include both Poisson uncertainties and the cosmic variance estimate (see Section 5.2). Our number counts are plotted along with the studies of Reddy et al. (2008), Sawicki & Thompson (2006), and Steidel et al. (1999). The only points corrected for completeness are the gold crosses for the Sawicki & Thompson (2006) data.

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

Poisson uncertainties for reference, while for the LRD we include both Poisson uncertainties and the fractional error per count of 0.2 to take into account the cosmic variance (see Section 5.2). The figure shows that we are photometrically complete to $V \sim 27$ mag, after which we start losing LBGs due to the sensitivity of the $u$-band image. In order to compare to other studies, we convert their $R$-band magnitudes from Keck to $V$-band magnitudes from HST with a $K$-correction at $z \sim 3$ for the Im galaxy template described in Section 4.1, which results in an $R$-$V$ color of $\sim -0.15$. The LBG number counts in Figure 13 of the LRD’s agree at the brighter end to within our uncertainties, however, at the fainter end ($V > 26.0$), our results are larger than the uncorrected KDF results, which is the only survey to probe to equivalent depths.
Based on the turnover in the LBG number counts in Figure 13, the KDF and our LRD study appear to be complete to \( V \gtrsim 26 \) and \( V \sim 27 \), respectively. The cumulative number counts for \( V < 26 \) is \( 3.7 \pm 0.6 \) LBGs arcmin\(^{-2}\) in our LRD study and \( 4.3 \pm 0.2 \) LBGs arcmin\(^{-2}\) for the KDF, where the uncertainties are Poisson. These results are consistent with each other, without invoking cosmic variance, and suggest that the difference in number counts for \( V \gtrsim 26 \) is due to differing completeness limits.

In order to understand this better, we also include the KDF number counts corrected for LBG completeness in Figure 13. This completeness correction is different than the one applied in (Sawicki & Thompson 2006), as it previously included the volume correction simultaneously. The correction applied here assumes that all \( z \sim 3 \) LBGs are well-represented by the colors of a fiducial LBG with (1) fixed age of 100 Myr (2) a fixed redshift \( z = 3 \), and (3) Calzetti et al. (1994) dust extinction for \( E(B-V) = 0.2 \). The incompleteness is then calculated by planting objects with these colors in the KDF images and determining how many are recovered, with the uncertainties estimated via bootstrap resampling (M. Sawicki 2009, private communication). This is not as careful a correction as applied in (Sawicki & Thompson 2006), but serves to investigate the completeness differences in our studies with respect to LBG detection. Our LRD study number counts are consistent with the KDF LBG completeness corrected number counts down to \( V \sim 27 \). This helps reinforce that we are likely complete in detecting \( z \sim 3 \) LBGs to \( V \sim 27 \) magnitude, making our study the deepest to date.

6. SUMMARY

We use newly acquired ground-based \( u \)-band imaging with a depth of 30.7 mag arcsec\(^{-2}\) (1\( \sigma \), sky fluctuations) and an isophotal limiting \( u \)-band magnitude of 27.6 mag to create a reliable sample of 407 \( z \sim 3 \) LBGs in the Hubble UDF. We use the template-fitting method TFIT (Laidler et al. 2007) to measure accurate photometry without the need for aperture corrections, and obtain robust colors across the largely varying PSFs of the UDF ACS images (0.09 FWHM) and the \( u \)-band image (1.3 FWHM). The results are as follows.

1. We calculate photometric redshifts for 1457 galaxies using the Bayesian algorithm of Benitez (2000), Benitez et al. (2004), and Coe et al. (2006), of which 1384 are reliable with \( \chi_{\text{mod}}^{2} < 4 \). We find that the previous photo-z's by Coe et al. (2006) do a good job of determining redshifts even without the \( u \) band if their uncertainties are taken into account. However, these uncertainties are often quite large at \( z \sim 3 \) due to the color degeneracy of \( z \sim 3 \) and \( z \sim 0.2 \) galaxies.

2. The \( u \) band significantly improves \( z \sim 3 \) photo-z determinations: out of 1384 galaxies, 175 galaxies no longer have degenerate photo-z's, and 125 of the galaxies changed their primary photo-z with the addition of the \( u \) band. In fact, the addition of the \( u \) band changed the photo-z's of \( \sim 50\% \) of the \( z \sim 3 \) galaxy sample.

3. We find that when using the \( u \)-band photometry and restricting the sample of photo-z's to those with good \( \chi_{\text{mod}}^{2} \); catastrophic photo-z errors can still occur, although they are rare (only 1 out of 93 galaxies with spectroscopic redshifts and photometric redshifts with \( \chi_{\text{mod}}^{2} < 4 \) and ODDS > 0.99). We found no catastrophic photo-z's in the redshift interval of interest, (2.5 \( \lesssim z \lesssim 3.5 \)), although only five objects have spec-z's in this interval. In contrast, three galaxies at 2.5 \( \lesssim z \lesssim 3.5 \) had catastrophic photo-z's before the addition of the \( u \) band.

The contamination fraction of the \( z \sim 3 \) photo-z sample is likely small as we sample the Lyman break for these galaxies, and show excellent spectroscopic agreement. However, given the small numbers, the overall error rate of the photo-z's is not well defined.

4. We find excellent agreement of our color-selected sample with the spectroscopic \( z \sim 3 \) sample, with no low-redshift galaxies falling in our color selection area, confirming our chosen criteria. We specifically choose a conservative color criteria that are equal or more conservative than the cuts of Steidel et al. (2003) such that we can infer that the \( \sim 3\% \) contamination fraction for \( z \sim 3 \) LBGs of Steidel et al. (2003) and Reddy et al. (2008) applies to our data set.

5. The completeness of our LBG selection depends largely on the \( u \)-band depth because the ACS bands from \( HST \) are deeper. In order to characterize this completeness, we compare our color-selected LBGs with other studies and find that we present the deepest sample of \( z \sim 3 \) LBGs currently available, likely complete to \( V \sim 27 \) mag.

This reliable sample of \( z \sim 3 \) LBGs can be used to further the studies of LBGs and star formation efficiency of gas at \( z \sim 3 \) through the most sensitive high-resolution images ever taken; the Hubble Ultra Deep Field.

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