DISCOVERY OF $z \sim 8$ GALAXIES IN THE HUBBLE ULTRA DEEP FIELD FROM ULTRA-DEEP WFC3/IR OBSERVATIONS∗

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ABSTRACT

We utilize the newly acquired, ultra-deep WFC3/IR observations over the Hubble Ultra Deep Field (HUDF) to search for star-forming galaxies at $z \sim 8$–8.5, only 600 million years from recombination, using a $Y_{105}$-dropout selection. The new 4.7 arcmin2 WFC3/IR observations reach to $\sim 28.8$ AB mag (5σ) in the $Y_{105}, J_{125}, H_{160}$ bands. These remarkable data reach $\sim 1.5$ AB mag deeper than the previous data over the HUDF, and now are an excellent match to the HUDF optical ACS data. For our search criteria, we use a two-color Lyman break selection technique to identify $z \sim 8$–8.5 $Y_{105}$-dropouts. We detect five likely $z \sim 8$–8.5 candidates. The sources have $H_{160}$-band magnitudes of $\sim 28.3$ AB mag and very blue UV-continuum slopes, with a median estimated $\beta$ of $\lesssim -2.5$ (where $f_{\lambda} \propto \lambda^\beta$). This suggests that $z \sim 8$ galaxies are not only essentially dust free but may have very young ages or low metallicities. The observed number of $Y_{105}$-dropout candidates is smaller than the 20 ± 6 sources expected assuming no evolution from $z \sim 6$, but is consistent with the five expected extrapolating the Bouwens et al. luminosity function (LF) results to $z \sim 8$. These results provide evidence that the evolution in the LF seen from $z \sim 7$ to $z \sim 3$ continues to $z \sim 8$. The remarkable improvement in the sensitivity of WFC3/IR has enabled Hubble Space Telescope to cross a threshold, revealing star-forming galaxies at $z \sim 8$–9.

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

1. INTRODUCTION

An important uncharted frontier is understanding how galaxies build up and evolve from the earliest times. While great progress has been made in characterizing the galaxy population at $z \lesssim 6$, extending these studies to $z \gtrsim 7$ has proven extraordinarily challenging. Only $\sim 25$ high-quality $z \sim 7$ galaxies are known (e.g., Bouwens et al. 2008; Oesch et al. 2009; Ouchi et al. 2009; Castellano et al. 2009; Gonzalez et al. 2009; R. J. Bouwens et al. 2010, in preparation). Fundamentally, the challenge has been to obtain extremely deep observations in the near-IR, where the redshifted UV light of faint $z \lesssim 7$ galaxies is found.

Now, with the installation of the WFC3/IR camera on the Hubble Space Telescope (HST), we have a far superior surveying instrument, with $6 \times$ the area of NICMOS, $2 \times$ the resolution, and $2 \times 4$ the sensitivity. These capabilities allow us to search for $z \gtrsim 7$ galaxies $\sim 40 \times$ more efficiently.

In the early WFC3/IR observations over the Hubble Ultra Deep Field (HUDF) to search for galaxies at $z \gtrsim 8$. This is the same epoch in which a gamma-ray burst was recently discovered at $z \approx 8.2$ (e.g., Salvaterra et al. 2009; Tanvir et al. 2009). Throughout this work, we quote results in terms of the luminosity $L_{\nu,z=3}^{\text{stellar}}$ (Steidel et al. 1999) derived at $z \sim 3$, i.e., $M_{\text{stellar,AB}} = -21.07$. We refer to the F606W, F775W, F850LP, F105W, F125W, and F160W bands on HST as $V_{606}, i_{775}, z_{850}, Y_{105}, J_{125}$, and $H_{160}$, respectively, for simplicity. Where necessary, we assume $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$. All magnitudes are in the AB system (Oke & Gunn 1983).

2. HUDF WFC3/IR OBSERVATIONS

The present high-redshift galaxy searches utilize the first epoch of ultra-deep near-IR WFC3/IR observations acquired over the HUDF (Beckwith et al. 2006) for the 192-orbit HUDF09 program (GO11563). This program will create three ultra-deep WFC3/IR fields, one positioned over the HUDF and the other two over the HUDF05 fields (Oesch et al. 2007), each imaged in three near-IR bands $Y_{105}, J_{125}$, and $H_{160}$. Combining these ultra-deep near-IR data with the similarly deep optical HUDF data permits us to select $z \sim 7$ $z_{850}$, $z \sim 8$ $Y_{105}$, and even $z \sim 10$ $J$ dropout galaxies to very low luminosities (i.e., $\sim 18$ AB mag, $\sim 0.06 L_\text{sun}$).

The WFC3/IR field over the HUDF is centered on $3^h32^m38.5^s$ and $-27^d47'00"$. In the first year of observations, we obtained 16 orbits of $Y_{105}$-band data (two orbits were severely impacted by persistence and are not included), 16 orbits of $J_{125}$-band data, and 28 orbits of $H_{160}$-band data. The sixty-orbit observations were obtained from 2009 August 26 to 2009 September 6.

Standard techniques were used to reduce the HUDF09 WFC3/IR imaging data. Individual images—after masking out sources—were median stacked to create super median images (one per filter) and these median images were then subtracted from the individual frames. The images were then aligned and drizzled onto the same grid as the v1.0 HUDF ACS data (Beckwith et al. 2006) rebinned on a 0.06-pixel scale. The drizzling

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was done using a modified version of multidrizzle (Koekemoer et al. 2002). 4σ outliers were rejected.

Given that the WFC3/IR instrument is still relatively new, we initially made our own estimates of the photometric zero points by performing point-spread function (PSF)-matched photometry on sources present in both the new observations and the HUDF NICMOS observations (e.g., Thompson et al. 2005; Bouwens et al. 2008; Oesch et al. 2009). The zero points derived were consistent (<0.05 mag) with the official STScI values, so we elected to use the STScI values 26.27, 26.25, and 25.96 mag for the Y105, J125, and H160 bands, respectively. The approximate 5σ depths of the Y, J, and H WFC3/IR images are 28.8, 28.8, and 28.8 mag, respectively, in 0′′.4 diameter apertures. ~1.5 mag deeper than the NICMOS data over the HUDF (Thompson et al. 2005). These depths were estimated by measuring the noise statistics in apertures of various size. The FWHM of the PSF in our WFC3/IR near-IR images is ~0′′.16. For reference, the HUDF optical B435V606I775z850 data (Beckwith et al. 2006) reached to 29.4, 29.8, 29.7, and 29.0 AB mag (5σ: 0′′.35-diameter apertures) and had PSF FWHMs of ~0′′.10.

3. OBJECT DETECTION AND VERIFICATION

3.1. Catalog Construction

Our procedure for doing object detection and photometry is identical to that used in previous work (e.g., Bouwens et al. 2007, 2008) and is performed using Sextractor (Bertin & Arnouts 1996; run in dual-image mode) on the registered data. Object detection is done from the co-added J125- and H160-band image (explicitly, using the square root of the χ2 image: Szalay et al. 1999), both of which are redward of the break for Y105-dropout galaxies. After smoothing the optical data to match the WFC3/IR PSFs, colors are measured using Kron (1980) style photometry in small apertures that scale with the size of the source (for Kron factors of 1.2). Flux measurements in these small apertures are corrected up to total magnitudes using the flux in larger scalable apertures (Kron factors of 2.5). This correction to total magnitudes (see, e.g., Figure 5 from Coe et al. 2006) is done on a source by source basis, based on the square root of χ2 image (approximately proportional to the co-added flux). Finally, the total magnitudes were corrected by 0.1 mag to account for light on the wings of the PSF.

3.2. Dropout Selection

Sources are selected over 4.7 arcmin2 with the deepest WFC3/IR observations (≤10% of this area is not at the full depth). The selection criteria we adopt for identifying z ~ 8 Y105 dropout galaxies are simple analogs of the criteria used to select Lyman break galaxies at lower redshift (e.g., Steidel et al. 1996; Giavalisco et al. 2004; Bouwens et al. 2007). That is, we require galaxies to show strong breaks (Y105 − J125 > 0.8) at the redshifted position of Lyα at z ~ 8 and to be blue redward of the break, i.e., (J125 − H160 < 0.5) and (J125 − H160 < 0.2 + 0.12(Y105 − J125)) to exclude intrinsically red galaxies at lower redshift (Figure 1). We also require our Y105-dropout candidates to show no detection (< 2σ: color-measurement aperture) in all bands blueward of the dropout band, i.e., B435V606I775z850. Sources showing α > 1.5σ detection in > 1 optical band were also eliminated. All of our Y105-dropout candidates were required to be 5.5σ detections in the J125 band to ensure they corresponded to real sources. We elected to use a 5.5σ criterion to be conservative for these early WFC3/IR data.

The most stringent aspect of the current selection is our requirement that sources be undetected in the ultra-deep HUDF optical data (which reaches to 31.5–32.0 at 1σ for most sources). From our simulations (Section 3.4), this requirement eliminates almost all contamination from sources at z ≤ 6, and hence we can use a modest (Y105 − J125) > 0.8 break to select z ~ 8 galaxies, without significant contamination concerns.

3.3. Y105-dropout Sample

We identify five sources that satisfy our Y-dropout criteria. The position of these sources in the Y105 − J125/J125 − H160 two-color plane is shown in Figure 1. The J125 − H160 colors of our Y105-dropout candidates are very blue in general, corresponding to UV-continuum slopes β of ≲ −2 (where fλ ∝ λβ), with a median β ≲ −2.5 (though we emphasize the number of sources are still small and the inferred βs may be affected by uncertainties in the photometry). The observed βs are blue enough that z ≥ 7 galaxies must be essentially dust free, and possibly also have very young ages or metallicities (see also Bouwens et al. 2010).

Cutouts of the sources are provided in Figures 1–3. The candidates have H160,AB band magnitudes of ~28.0–29.0 AB mag, within 1 mag of our sensitivity limit. Such sources could not have been found to date since they are fainter than could be probed with other data sets. This illustrates the importance of the very deep near-IR data being collected as part of the HUDF09 program.

All five candidates have apparent half-light radii of ~0′′.15 (~0.7 h−1 kpc)—measured using Sextractor—not much larger than the PSF. The four candidates—for which crowding is not a concern—do not show significant (>2σ) detections in the IRAC data over the GOODS fields either individually or when stacked (Labbé et al. 2010). The non-detection of the candidates in the IRAC data is not particularly surprising given the much shallower depths of the IRAC data (~27.0 AB mag at 2σ) relative to the WFC3/IR data.

3.4. Contamination Corrections

The only meaningful source of contamination for the present sample are objects that enter the selection via photometric scatter. A simple estimate of the likely contamination can be obtained by adding noise to the color distribution observed for ~25–26.5 AB mag galaxies. The advantage of using this color distribution for the simulations is that the distribution is realistic (being taken from the observations), has a higher signal-to-noise ratio than fainter magnitudes, and does not include any any z ≥ 7.5 galaxies. We find ≤0.2 contaminants per field, suggesting such a source of contamination is minimal (≤4%).

The <4% contamination estimate implicitly includes the contribution of z ~ 1.5–2 Balmer break galaxy (BBG) sources scattered into our selection. We expect the explicit contribution to be small given the lack of faint sources with V − J > 1.5, J − H > 0.15 colors expected for BBGs (arbitrary reddenings, metallicities: R. J. Bouwens et al. 2010, in preparation).

Other sources of contamination are not important for this selection. For example, given that each source is detected at ≥5.5σ in the J125 band and >4σ in the H160 band, no contamination from spurious sources is expected. Contamination by supernovae is also not important, given that the Y105, J125, H160...
data were taken over the same twelve-day window. Finally, contamination by stars is also unlikely. Not only are T dwarfs rare over the CDF-South, with a surface density $\lesssim 0.04$ arcmin$^{-2}$ (e.g., Bouwens et al. 2008) and therefore unlikely to be found in our 4.7 arcmin$^2$ field, but also all five of our candidates appear to be extended (having SExtractor stellarity parameters $< 0.3$; see also Oesch et al. 2010b) and hence not likely to be stars.

4. RESULTS AND IMPLICATIONS

4.1. Expected Numbers

To interpret the results of the present $z \sim 8$ $Y_{105}$-dropout selection, it is useful to estimate how many $Y_{105}$-dropouts we might have expected if the UV luminosity function (LF) showed no evolution from $z \sim 6$ and $z \sim 7$. We estimate the numbers by creating galaxy catalogs according to the model LFs, adding artificial galaxies to the data, and then processing the images and doing the selection in the same way as for the real data. For these simulations, we model the pixel-by-pixel profiles of galaxies at $z \sim 8$ with similar-luminosity galaxies from the $z \sim 4$ Bouwens et al. (2007) HUDF B dropout sample, but scaled in size to match the observed $(1+z)^{-1}$ size--redshift scaling (Oesch et al. 2010b; Bouwens et al. 2004, 2006; Ferguson et al. 2004). Star-forming galaxies at $z \sim 7$--9 are assumed to have mean UV-continuum slopes $\beta$ of $-2.5$, with a $1\sigma$ scatter of 0.4, to match the apparent colors of $Y_{105}$-dropouts in our sample (see Figure 1).

Adopting the $z \sim 6$ $i$-dropout LF from Bouwens et al. (2007; see also McLure et al. 2009) and assuming no evolution to higher redshift, we predict $20 \pm 6$ $Y_{105}$-dropouts in our WFC3/IR field. The $z \sim 6$ predictions are shown as a function of $H_{160}$-band magnitude in Figure 4 (lower panel) and compared with the observations. We expect $\sim 70\%$ uncertainties in these numbers due to small number statistics and large-scale structure variations (assuming a $4.7$ arcmin$^2$ survey field, $\Delta z \sim 0.8$ redshift selection window, and $\sim 10^{-3}$ Mpc$^{-3}$ source density; e.g., Trenti & Stiavelli 2008). The observed numbers are $> 2\sigma$ lower than expected from the well-determined $z \sim 6$ LF. Predicted surface densities can also be made using the Bouwens et al. (2008) $z \sim 7$ LF (also shown), but the uncertainties are large given the small sample in that paper (and the new WFC3/IR observations permit much better $z \sim 7$ LF estimates).
4.2. Implications for the z ~ 8 UV LF

The fact that the observed numbers are lower than predicted assuming no evolution from z ~ 6 suggests that the UV LF continues to evolve from z ~ 8. So, it is interesting to extrapolate the LF results from Bouwens et al. (2008) to z ~ 8 — giving $M_{UV}^{*} = -19.45$, $\phi^{*} = 0.0011$ Mpc$^{-3}$, and $\alpha = -1.74$ — and see what we find. Performing this exercise, we predict that five $Y_{105}$-dropouts would be found in the present search (shown with the dotted black line in the lower panel of Figure 4). This is in good agreement with the observed results.

We can further quantify the overall magnitude of this evolution. Using the Bouwens et al. (2008) LF parameterization as a guide, we fix $\alpha = -1.74$, $\phi^{*} = 0.0011$ Mpc$^{-3}$, and then derive confidence intervals on $M_{UV}^{*}$. For our $Y_{105}$-dropout search, we estimate that $M_{UV}^{*} = -19.5 \pm 0.3$ AB mag. This is significantly fainter than the $M_{UV}^{*} = -20.2 \pm 0.2$ AB mag estimated at $z ~ 6$ or the $M_{UV}^{*} = -21$ AB mag at $z ~ 4$.

Of course, given the size of the sample and lack of complementary wide-area searches for bright $z ~ 8$ sources, it is difficult to constrain the shape of the $z ~ 8$ UV LF. Therefore, we simply consider the stepwise LF at $z ~ 8$. We divide our dropout sample into 0.5 mag bins, compute the equivalent absolute magnitudes in each of these bins, and then divide the observed number of sources in each bin by the effective selection volume, which are estimated using the same simulations described in Section 4.1. These stepwise LF determinations are presented in Figure 4, with the LFs at $z ~ 4–7$ (Bouwens et al. 2007; Oesch et al. 2010a) shown for context. The 1σ upper limits on the volume density of luminous $z ~ 8$ sources are also shown. It would appear that the UV LF only shows very weak evolution at low luminosities ($\sim -18.3$ AB mag). This is in contrast to the dramatic evolution observed at the bright end from $z ~ 7$ to $z ~ 4$ (see, e.g., the discussion in Shimasaku et al. 2005; Bouwens et al. 2008).

4.3. Constraints on the UV Luminosity Density/SFR Density at z ~ 8

Finally, we calculate the luminosity densities (and unobscured star formation rate (SFR) densities) at $z ~ 8$ implied by these constraints on the rest-frame UV LF. For the luminosity density at $z ~ 8$, we simply integrate the stepwise $z ~ 8$ LF shown in Figure 4. We convert these UV luminosity densities into the equivalent unobscured SFR densities using the Madan et al. (1998) prescription. Our results for UV luminosity densities and SFR densities (all integrated down to $-18.3$ AB mag, or 0.08 $L^{*}_{1\mu m}(-18.3$ AB mag)) can be summarized as follows: for the $z ~ 8$ Y-dropout sample, the luminosity density is $25.18 \pm 2.73 \times 10^{-18} \text{ erg s}^{-1} \text{ Hz}^{-1} \text{ Mpc}^{-3}$, and the SFR density is $3.13 \pm 0.34 \times 10^{-23} \text{ M}_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$, respectively. The units on the luminosity and SFR densities (both comoving) are erg s$^{-1}$ Hz$^{-1}$ Mpc$^{-3}$ and $M_{\odot}$ Mpc$^{-3}$ yr$^{-1}$, respectively. The dust correction is taken to be 0, given the very blue β (see also Bouwens et al. 2009, 2010). The results are also presented in Figure 5.
As these results demonstrate, the remarkable improvement in the sensitivity and the “discovery efficiency” (area gain × sensitivity gain) of WFC3/IR has enabled HST to cross a threshold. HST can now find star-forming galaxies at $z \sim 8–8.5$. The existence of such galaxies and the active star formation implied at even higher redshifts $z > 10$ provides a striking framework for future detailed James Webb Space Telescope observations.

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