ABSTRACT

We have detected likely $z \sim 7$–8 galaxies in the 144$^{\prime\prime}$ × 144$^{\prime\prime}$ Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) observations of the Hubble Ultra Deep Field. Objects are required to be $\geq 3\sigma$ detections in both NICMOS bands, $J_{110}$ and $H_{160}$. The selection criteria for this sample are $(z_{850} - J_{110})_{AB} > 0.8$, $(z_{850} - J_{110})_{AB} > 0.66(J_{110} - H_{160})_{AB} + 0.8$, $(J_{110} - H_{160})_{AB} < 1.2$ and no detection at less than 8500 Å. The five selected sources have total magnitudes $H_{160, AB} \sim 27$. Four of the five sources are quite blue compared to typical lower redshift dropout galaxies and are clustered within a 1 arcmin$^2$ region. Because all five sources are near the limit of the NICMOS data, we have carefully evaluated their reality. Each of the candidates is visible in different splits of the data and a median stack. We analyzed several noise images and estimate the number of spurious sources to be $\pm 1$. A search using an independent reduction of this same data set clearly revealed three of the five candidates and weakly detected a fourth candidate, suggesting that the contamination could be higher. For comparison with predictions from lower redshift samples, we take a conservative approach and adopt four $z \sim 7$–8 galaxies as our sample. With the same detection criteria on simulated data sets, assuming no evolution from $z \sim 3$, we predict 10 sources at $z \sim 7$–8, or 14 if we use a more realistic $(1 + z)^{-1}$ size scaling. We estimate that the rest-frame continuum UV (\sim 1800 Å) luminosity density at $z \sim 7.5$ (integrated down to $0.3L_{*21}$) is just $0.20^{+0.12}_{-0.12}$ times that found at $z \sim 3.8$ (or $0.20^{+0.23}_{-0.12}$ times this quantity including cosmic variance). Effectively this sets an upper limit on the luminosity density down to $0.3L_{*21}$ and is consistent with significant evolution at the bright end of the luminosity function from $z \sim 7.5$ to 3.8. Even with the lower UV luminosity density at $z \sim 7.5$, it appears that galaxies could still play an important role in reionization at these redshifts, although definitive measurements remain to be made.

Subject headings: galaxies: evolution — galaxies: high-redshift

1. INTRODUCTION

From the spectroscopic identification of a population of $z \sim 3$ dropouts (Steidel et al. 1996) to recent work on i-dropouts (Yan et al. 2003; Stanway et al. 2003; Bouwens et al. 2003b; Dickinson et al. 2004), the frontier for high-redshift galaxy studies is continually being redefined. In this Letter, we extend this frontier to $z \sim 7$ and beyond by performing a $z_{850}$ dropout search over the area of the Hubble Ultra Deep Field (S. V. W. Beckwith et al. 2004, in preparation) with deep Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) coverage (R. I. Thompson et al. 2004a, in preparation). The exceptional depth of both the optical and the infrared data makes this area ideal for carrying out such a search, reaching to 29.5, 29.7, 29.4, 28.8, 27.6, and 27.4 (5 σ, 0.6 diameter apertures) in the F435W, F606W, F775W, F850LP, F110W, and F160W bands (hereafter $B_{435}$, $V_{606}$, $I_{775}$, $z_{850}$, $J_{110}$, and $H_{160}$, respectively). Previously, this redshift range had been probed by a $z_{850}$ dropout search in the Hubble Deep Field–North (Dickinson 2000) and similar dropout searches around lensing clusters (Kneib et al. 2004; Pelló et al. 2004). All magnitudes are expressed in the AB system. We assume $(\Omega_m, \Omega_\Lambda, h) = (0.3, 0.7, 0.7)$ (Bennett et al. 2003).

2. ANALYSIS

Our search area was the 0.099 pixel $144^{\prime\prime} \times 144^{\prime\prime}$ NICMOS mosaic (R. I. Thompson et al. 2004a, in preparation). Sources were identified in the summed $J + H$ image (R. I. T) and the $\chi^2$ (Szalay et al. 1999) image (R. J. B.) using the SExtractor code (Bertin & Arnouts 1996). Colors were calculated using a scaled aperture Kron magnitude (Kron 1980) with the Kron factor equal to 1.2. Total magnitudes were then derived using the $\chi^2$ image to correct these fluxes to a much larger aperture (where the Kron factor was equal to 2.5; see Bouwens et al. 2003a). Typical corrections were $\sim 0.8$ mag for each object.

1. $z_{850}$-dropout selection.—Objects were required to be null detections ($\leq 2\sigma$) in the deepest ($V_{606}$ and $I_{775}$) optical bands (in 0.6 diameter apertures) and lie in the expected place \{$(z_{850} - J_{110}) > 0.8$, $(z_{850} - J_{110})_{AB} > 0.66(J_{110} - H_{160})_{AB} + 0.8$, $(J_{110} - H_{160})_{AB} < 1.2$\} in the standard two-color $z_{850} - J_{110}$/$J_{110} - H_{160}$ diagram. To clean our catalog of possible spurious detections, objects were required to be 3 σ detections (0.6 diameter aperture) in both the $J_{110}$ and the $H_{160}$ bands. These procedures identified a set of eight sources to a limiting magnitude of $H_{160, AB} \sim 28$. A separate selection by R. I. T identified a similar set of objects. After identification, each source was located in the original exposures (16 in each band) to ensure that they did not arise from a small subset of the exposures (e.g., from a pre-integration cosmic-ray hit). Three of our eight sources were rejected, as they were visible in only a couple of exposures. The five real sources are shown in Figure 1 and Table 1.
Candidates appear to be rather clustered, with four of the five objects shown as black squares (2σ lower limits are indicated by vertical arrows). These objects are not detected in the optical and bands. The cyan squares that lie in the selection region have clear detections (≥2σ) and so are not candidate dropouts; a representative error bar (cyan) for these objects is shown at the right center of this diagram. The color-color tracks of both lower redshift interlopers (red lines) and 108 yr starburst spectral energy distributions with different reddenings (green crosshatched region; G. R. Knapp et al. 2004, in preparation). Error bars on the z850 − J110 and J110 − H160 colors are 1σ.

Table 1 includes the photometric information for our five candidates plus one red galaxy that nearly met our criteria (this latter object was also found by Yan & Windhorst 2004). Candidates had H160,AB magnitudes ranging from 26.0 to 27.3, or 0.5–1.5 times the characteristic rest-frame UV luminosity (L∗) for Lyman break galaxies at z ∼ 3 (Steidel et al. 1999). Candidates appear to be rather clustered, with four of the five candidates falling within a ∼1 arcmin2 area. Figure 2 displays postage stamp images of each candidate.

2. Testing source reality.—Our five candidates were then subjected to several additional tests. Each source was verified to exist at the greater than 2.5σ level in the J + H image for each of the two epochs (taken 2 months apart and at a 90° angle to each other). Each source was also evident (>2.4σ) in a median stacking of the 16 overlapping exposures for each band. This is useful, since the median process should eliminate sources with flux in only a few exposures. After performing the above sanity checks on our candidates, we repeated our selection procedure on three different image sets to examine the likelihood that our candidates are simply spurious detections. These three images include the “negative” images, the first epoch images subtracted from the second epoch images, and the second epoch images subtracted from the first. These images should have similar noise characteristics to the data but contain no real sources. Only one, two, and zero objects, respectively, were found on each of the above three image sets (5.76 arcmin2) using an identical selection procedure. This suggested a small level of contamination from spurious sources (1 ± 1 object) in the current sample.

3. An independent check on source reality.—An independent reduction of the NICMOS images was kindly made available to us by R. I. T. by M. Robberto et al. (2004, in preparation). The image was inspected by R. I. T., and three of our five candidate sources clearly appear in those images. However, no signal is evident at the position of UDF-818-886, while UDF-491-880 is only weakly detected. Until this is resolved, the contamination may be higher than estimated above (§ 2, item 2).

4. Low-redshift contamination.—To test for possible contamination from low-redshift interlopers, we randomly assigned the colors of bright (23.5 < H160,AB < 25) objects from the Ultra Deep Field (UDF) to faint objects in our field, added photometric scatter, and then repeated our selection. No objects were found, suggesting minimal contamination from low-redshift interlopers. Possible contamination from T dwarfs was also considered, given their position in color-color space (Fig. 1) and predicted numbers (0.04–0.3 objects) over our field of view (Burgasser et al. 2004). However, this proved not to be a concern for our sample, since T dwarfs would appear as low-z objects. Possible contamination from T dwarfs was also considered, given their position in color-color space (Fig. 1) and predicted numbers (0.04–0.3 objects) over our field of view (Burgasser et al. 2004). However, this proved not to be a concern for our sample, since T dwarfs would appear as low-z objects.

5. Expected numbers/incompleteness tests.—It is interesting to compare the number of candidates against that predicted assuming no evolution from lower redshift. As in other recent work, we adopt a z ∼ 3.8 B-dropout sample from the GOODS fields (Bouwens et al. 2004b, hereafter B04) as our reference

**TABLE 1**

| Object ID  | Right Ascension | Declination | H160,CW   | H160,Ap1   | H160,Ap2   | z − J      | J − H      | S/G   | rArc   |
|------------|----------------|-------------|-----------|------------|------------|------------|------------|-------|--------|
| UDF-825-950 | 03 32 39.538 | -27 47 17.41 | 26.1 ± 0.3 | 27.3 ± 0.2 | 26.7 ± 0.2 | >2.1       | 0.5 ± 0.3  | 0.08  | 0.39   |
| UDF-491-880c | 03 32 40.941 | -27 47 41.83 | 26.6 ± 0.3 | 27.6 ± 0.3 | 26.9 ± 0.2 | >2.3       | 0.1 ± 0.3  | 0.03  | 0.34   |
| UDF-387-1125 | 03 32 42.565 | -27 47 31.42 | 26.6 ± 0.3 | 27.4 ± 0.2 | 27.6 ± 0.2 | 1.4 ± 0.4  | 0.8 ± 0.3  | 0.68  | 0.28   |
| UDF-983-964  | 03 32 38.794 | -27 47 07.14 | 27.1 ± 0.3 | 27.8 ± 0.3 | 27.1 ± 0.2 | >2.1       | 0.0 ± 0.3  | 0.48  | 0.27   |
| UDF-818-880  | 03 32 39.292 | -27 47 22.12 | 27.1 ± 0.3 | 27.6 ± 0.3 | 27.3 ± 0.3 | >2.0       | 0.2 ± 0.3  | 0.84  | 0.23   |
| UDF-640-1417d | 03 32 39.526 | -27 46 56.58 | 26.0 ± 0.3 | 27.1 ± 0.3 | 26.2 ± 0.5 | 1.1 ± 0.2  | 0.7 ± 0.2  | 0.11  | 0.37   |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

1 All magnitudes are AB magnitudes. Right ascension and declination use the J2000.0 equinox. Errors are 1σ. Limits on z850 − J110 colors are 2σ.

2 “SG” denotes the SExtractor stellarity parameter, for which 0 indicates an extended object and 1 a point source. “Cor” refers to a total magnitude estimated using the Kron system (see § 2). “Ap1” refers to a 0.56 diameter aperture magnitude, and “Ap2” refers to a 1.70 diameter aperture magnitude. The z − J and J − H colors were estimated in a Kron aperture with Kron factor equal to 1.2 (similar to the 0.56 diameter apertures used for Ap1).

3 These candidates are not found (UDF-818-886) or seen to lower significance (UDF-491-880) in an independent reduction of the NICMOS field kindly provided to us by M. Robberto et al. (2004, in preparation).

4 NICMOS images are known to have faint ghosts exactly 128 pixels from bright objects (Skinner et al. 1998). We note that one object in our candidate list (UDF-491-880) has almost exactly this offset from the bright star at 03h25m42.5s, −27°47′58.83″, and therefore may be an artifact.

5 This object was very close to meeting our selection criteria and could be a reddened starburst at z ∼ 6.5. Another possibility is that of a dusty/evolved galaxy at z ∼ 1.6. This object was also found by Yan & Windhorst (2004).
point and project it to \( z \approx 6-10 \) using our well-established cloning machinery (Bouwens et al. 1998a, 1998b, 2003a, B04). Such simulations are important for establishing the incompleteness, which can be as high as 75% for these \( z \approx 7-8 \) objects (this includes the effect of possible blending with foreground galaxies). Adding the cloned galaxies directly to the data, we repeat our selection procedure and thereby derive a no evolution prediction; this yields 10 dropouts. However, we know that galaxies evolve in size \( [1 + z]^{-1} \) size scaling for fixed luminosity; Bouwens et al. 2004a, 2004c; Ferguson et al. 2004] and hence surface brightness. Including this effect, 14 objects (this includes the effect of possible blending with foreground galaxies). The ACS cuts here are shown at a much higher contrast than the NICMOS cuts, demonstrating the significance of the optical nondetections. The postage stamps are \( 29^\prime \times 29^\prime \) in size. A linear stretch is used for scaling the pixel fluxes.

3. LUMINOSITY DENSITY AND IMPLICATIONS

We can now compare the observations with the predictions made earlier (§ 2, item 5). This permits us to set important constraints on the evolution at the bright end of the luminosity function (LF) in rest-frame continuum UV (\( \sim 1800 \) Å) and therefore make inferences about changes in the luminosity density. To be conservative, we assume that the number of \( z_{850} \) dropouts is four. Given possible concerns about their validity (§ 2, items 2, 3, and 6), we also consider the implications if there are even fewer sources. For the expected number of \( z_{850} \)-dropouts, we use 14, the prediction from the \( (1 + z)^{-1} \) size scaling (§ 2, item 5).

Comparing our four fiducial candidates with the 14 objects predicted suggests that the number of objects at the bright end of the LF at \( z \approx 7.5 \) is just 0.29 times that at \( z \approx 3.8 \) (Fig. 3). This decreases to 0.14 times and less than 0.13 times (1 \( \sigma \)) if only two or none of our candidates are real, respectively. Obviously, there are substantial uncertainties in the estimated shortfall, as a result of both the small number statistics and the expected cosmic variance (factor of 2; assuming a cold dark matter power spectrum normalized to high-redshift observations and a redshift selection window of unit width; e.g., Somerville et al. 2004). Therefore, even no evolution is consistent with the present result at the 1.5 \( \sigma \) level.

While a number of options are open, the most likely case is a drop of at least 3.5 times in the number of objects at the bright end of the LF. Since this is similar to what is found at \( z \approx 6 \) (Stanway et al. 2003, 2004a; Dickinson et al. 2004), it is likely a continuation of the same effect. A key question is whether the observed deficit continues all the way down the LF or if it is due to evolution in the characteristic luminosity \( (L^*) \) at high redshift. This whole issue is pivotal for questions about reionization, since it is at faint magnitudes that the bulk of the flux arises (assuming a steep \( \alpha \leq -1.5 \) faint-end slope). Fortunately, the fainter \( i^- \)-dropouts from the UDF are beginning to provide us with some clues, and some early studies are already suggesting that the principal form of the evolution is in luminosity or a steepening of the faint-end slope (Dickinson et al. 2004; Yan & Windhorst 2004; R. J. Bouwens et al. 2004d, in preparation; cf. Bunker et al. 2004). If true, this would provide a natural explanation for our shortfall and may allow for sub-
FIG. 3.—Top: Rest-frame continuum UV (∼1800 Å) luminosity density (integrated down to 0.3 $L_{\odot}$) vs. redshift. The observed luminosity density is converted to a star formation rate (uncorrected for extinction) assuming a Salpeter IMF (e.g., Madau et al. 1998). The present determination (assuming four candidates) is shown as the large red circle, with an upper limit shown to acknowledge possible concerns regarding several of our candidates. Previous determinations from Lilly et al. (1996; open squares), Steidel et al. (1999; green crosses), Giavalisco et al. (2004; filled black diamonds), Bunker et al. (2004; filled blue square), Bouwens et al. (2004a; filled magenta circles), and Bouwens et al. (2004b; filled red triangle) are also shown. The uncertainty expected from large-scale structure (cosmic variance) is ±20% for many of the lower redshift points (e.g., Somerville et al. 2004) and ±50% for the $z \sim 7.5$ point. The top horizontal axis provides the corresponding age of the universe. Bottom left: Surface density vs. total magnitude of the observed $z_{850}$-dropouts (histogram) and that predicted from a $(1 + z)^{−1}$ size scaling of our GOODS B-dropout sample (B04) (red, see § 2, item 5), demonstrating the evolution for bright galaxies. Bottom right: Expected redshift distribution for $z_{850}$-dropouts derived from these same simulations. Taken together, these results suggest a modest to significant decline in the star formation rate density (uncorrected for extinction: see R. I. Thompson et al. 2004b, in preparation, for the extinction-corrected star formation history) to $z \sim 7.5$.

stantial star formation at higher redshifts, as suggested by recent measurements from the Wilkinson Microwave Anisotropy Probe (Kogut et al. 2003) or the large stellar masses found in the $z \sim 6.5$ Kneib et al. (2004) object (E. Egami et al. 2004, in preparation). It would also suggest that for a proper census of these objects the present surveys need to be extended to considerably fainter magnitudes (with WFC3 and ultimately with the James Webb Space Telescope).

In light of the uncertainties regarding the form of the evolution, we have chosen simply to quote the evolution in luminosity density down to the total magnitude limit of our survey ($H_{160, AB} \sim 27.5$ or $\sim 0.3 L_{\odot}$). Conversions to star formation rate density (uncorrected for extinction) are made using the now canonical conversion factors for the Salpeter initial mass function (IMF; Madau et al. 1998). For both quantities (the luminosity density and the star formation rate), we infer a larger drop than above (due to luminosity-weighting; see Fig. 3). To the faint-end limit and including the Poissonian variations quoted above, we find that $\rho_{\text{UV}}(z = 7.5)/\rho_{\text{UV}}(z = 3.8) = 0.20^{+0.32}_{-0.09}$ using our fiducial list of candidates and $0.10^{+0.09}_{-0.05}$ and less than 0.05 (1 $\sigma$) assuming that only two or none of our candidates are real, respectively. Uncertainties on these quoted factors increase to $0.20^{+0.32}_{-0.12}$, $0.10^{+0.20}_{-0.07}$, and less than 0.11 (1 $\sigma$), respectively, including the expected field-to-field variations (cosmic variance) quoted above.

This is the first such deep sample ever compiled at $z \sim 7–8$ and allowed us to set interesting constraints on the bright end of the rest-frame UV-continuum LF at $z \sim 7.5$ during the epoch of reionization. The similarity of the present result with that at $z \sim 6$ (Stiavelli et al. 2004; Yan & Windhorst 2004) suggests that galaxies could have been an important contributor to reionization at these early times, although a characterization of their role warrants more definitive measurements.

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