THE UDF05 FOLLOW-UP OF THE HUBBLE ULTRA DEEP FIELD. II. CONSTRAINTS ON REIONIZATION FROM Z-DROPOUT GALAXIES\textsuperscript{*}

P. A. Oesch\textsuperscript{1}, C. M. Carollo\textsuperscript{1}, M. Stiavelli\textsuperscript{2}, M. Trenti\textsuperscript{2}, L. E. Bergeron\textsuperscript{2}, A. M. Koekemoer\textsuperscript{2}, R. A. Lucas\textsuperscript{3}, C. M. Pavlovsky\textsuperscript{1}, S. V. W. Beckwith\textsuperscript{2}, T. Dahlen\textsuperscript{2}, H. C. Ferguson\textsuperscript{2}, Jonathan P. Gardner\textsuperscript{3}, S. J. Lilly\textsuperscript{1}, B. Mobasher\textsuperscript{2}, and N. Panagia\textsuperscript{2,4,5}

\textsuperscript{1}Department of Physics, Institute of Astronomy, Eidgenössische Technische Hochschule (ETH Zurich), CH-8093 Zurich, Switzerland; poesch@phys.ethz.ch
\textsuperscript{2}Space Telescope Science Institute, Baltimore, MD 21218, USA
\textsuperscript{3}Laboratory for Observational Cosmology, Code 665, NASA's Goddard Space Flight Center, Greenbelt, MD 20771, USA
\textsuperscript{4}INAF-Osservatorio Astrofisico di Catania, Via S. Sofia 78, I-95123 Catania, Italy
\textsuperscript{5}Supernova Ltd., OYV 131, Northsound Road, Virgin Gorda, British Virgin Islands

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ABSTRACT

We detect three (plus one less certain) z\textsubscript{SS0}-dropout sources in two separate fields (Hubble Ultra Deep Field and NICP34) of our UDF05 Hubble Space Telescope Near-Infrared Camera and Multi-Object Spectrometer images. These z \sim 7 Lyman-break galaxy (LBG) candidates allow us to constrain the Luminosity Function (LF) of the star-forming galaxy population at those epochs. By assuming a change in only $M_*$ and adopting a linear evolution in redshift, anchored to the measured values at z \sim 6, the best-fit evolution coefficient is found to be 0.43 \pm 0.19 mag per unit redshift (0.36 \pm 0.18, if including all four candidates), which provides a value of $M_*(z = 7.2) = -19.7 \pm 0.3$. This implies a drop in the luminosity density in LBGs by a factor of \sim 2–2.5 over the \sim 170 Myr that separate z \sim 6 and z \sim 7, and a steady evolution for the LBG LF out to z \sim 7, at the same rate that is observed throughout the z \sim 3–6 period. This puts a strong constraint on the star-formation histories of z \sim 6 galaxies, whose ensemble star-formation rate (SFR) density must be lower by a factor of 2 at \sim 170 Myr before the epoch at which they are observed. In particular, a large fraction of stars in the z \sim 6 LBG population must form at redshifts well above z \sim 7. The rate of ionizing photons produced by the LBG population consistently decreases with the decrease in the cosmic SFR density. Extrapolating this steady evolution of the LF out to higher redshifts, we estimate that galaxies would be able to reionize the universe by z \sim 6, provided that the faint-end slope of the z > 7 LF steepens to $\alpha \sim -1.9$ and that faint galaxies with luminosities below the current detection limits contribute a substantial fraction of the required ionizing photons. This scenario, however, gives an integrated optical depth to electron scattering that is \textsuperscript{\sigma} \sim 0.35 mag per unit redshift over the z = 3–6 epoch. Therefore, altogether, our results indicate that, should galaxies be the primary contributors to reionization, either the currently detected evolution of the galaxy population slows down at z \gtrsim 7, or the LF evolution must be compensated by a decrease in metallicity and a corresponding increase in ionization efficiency at these early epochs.

Key words: galaxies: evolution – galaxies: formation – galaxies: high-redshift – galaxies: luminosity function, mass function

Online-only material: color figures

1. INTRODUCTION

One of the most fundamental open issues in observational cosmology is what sources reionized the early Universe. Since the z \gtrsim 6 quasar luminosity function (LF) is found to be too shallow to provide enough ionizing photons (e.g., Fan et al. 2001; Meiksin 2005; Shankar & Mathur 2007), the most likely culprits are thought to be galaxies. A key question, therefore, is how the star-forming galaxy population evolves beyond the putative end of reionization at z \sim 6, that is, well into the epoch of reionization.

Direct searches for Ly\alpha emission provide a powerful way to study high-redshift galaxies (e.g., Iye et al. 2006; Stark et al. 2007; Ota et al. 2008); however, it is difficult to estimate the (continuum and) ionizing flux of Ly\alpha emitters, and thus their contribution to reionization. A more fruitful approach is provided by the Lyman break technique.

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Thousands of Lyman-break galaxies (LBGs) have been identified between z \sim 3 and 6 from optical images, providing an estimate for the rest-frame UV LF at those redshifts (e.g., Oesch et al. 2007, hereafter O07; Bouwens et al. 2007, hereafter B07; also see Steidel et al. 1999; Sawicki & Thompson 2006; Yoshida et al. 2006; Iwata et al. 2007). The evolution of the LBG LF throughout this redshift range is, however, still being debated—in particular, at the bright end, the strong clustering of bright galaxies and the tiny area coverage of space-based images prevent setting strong constraints on the LF. Another important factor is that the number of spectroscopically confirmed LBGs is still small due to the faintness of the sources. Within these caveats, O07 and B07 have published independent, self-consistent analyses, which agree on a remarkably steady evolution of $\Delta M_\ast \sim 0.35$ mag per unit redshift over the z = 3–6 epoch.

At redshifts z > 6, the rest-frame Ly\alpha line shifts into the near-infrared (NIR), and the relatively low efficiency and small field of view (FOV) of current NIR detectors have limited the identification of LBGs. Thus, in contrast to the large number of sources detected out to z \sim 6, the numerous searches for z \gtrsim 7 LBGs has led to only a handful of candidates (e.g., Bouwens...
et al. 2008, hereafter B08; Mannucci et al. 2007; Bouwens & Iltingworth 2006; Yan & Windhorst 2004; Stanway et al. 2008). Searches for intrinsically faint $z \gtrsim 7$ LBGs around lensing clusters also resulted only in small numbers of candidates (e.g., Richard et al. 2006, 2008; Bradley et al. 2008), due to the small areas subject to the lensing magnification.

One of the most comprehensive studies is the recent analysis of B08, who have measured the $z \sim 7$ LBG LF from a large compilation of both Hubble Space Telescope (HST) and ground-based data, covering a total area of $\sim 271$ arcmin$^2$ over the two fields of the GOODS survey (Giavalisco et al. 2004). Again, within the caveats imposed by probing, with small number statistics, only the bright end of the LF, these authors reported that the dimming of the LBG LF, which has been measured out to $z \sim 6$, continues with no substantial change out to $z \sim 7$.

A summary of the previous work in the context of reionization is that, albeit within some restrictive assumptions, the detected $z \sim 7$ LBG population appears to be just barely able to maintain the Universe ionized (e.g., Ferguson et al. 2002; Lehnert & Bremer 2003; Stiavelli et al. 2004; Bunker et al. 2004; Bouwens & Iltingworth 2006; Gnedin 2008a), and also the detected $z \sim 7$ LBGs fall short of being able to provide the photons required to reionize the Universe (Bolton & Haehnelt 2007). It seems that fainter galaxies must have played a very important role (e.g., Yan & Windhorst 2004; Richard et al. 2008).

Here we present our independent derivation of constraints on the $z \sim 7$ LBG LF. This is desirable in order to independently check the different effects of various uncertainties in the process of estimating LFs, including the data reduction, object detection, and the estimation of effective selection volume. We use our UDF05 data and the optical (Beckwith et al. 2006) and NIR (Thompson et al. 2005) data of the Hubble Ultra Deep Field (HUDF). The UDF05 survey is a 204 orbit, HST Large Program of the ultradeep Advanced Camera for Surveys (ACS) and Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) observations of multiple fields, each located $\sim 10\,''$ away from HUDF (see 007). The UDF05 was designed to image with ACS-Wide Field Channel (WFC) the two NICMOS parallel fields (hereafter, NICP12 and NICP34) that were acquired while the HUDF was observed with the ACS, thus facilitating a reliable search for $z > 6$ galaxies in these fields to unprecedented depths.

The combined NIR NICMOS data set that we study in this paper consists of three fields, covering a total area of 7.9 arcmin$^2$, with $5\sigma$ point-source magnitude limits varying between 27.9 and 28.8 in F160W ($H_{160}$) and 27.6 and 28.6 in F110W ($J_{110}$). The 50% completeness limits vary between 26.9 and 28.1 mag (see Table 1 and Section 3.1). Each of the fields consists of one deep pointing and one slightly shallower flanking area (by $\sim 0.6$ mag). These data, also used in B08, provide the deepest NIR data available to date.

In Section 2, we describe the data and the steps adopted to identify the $z \sim 7$ LBG candidates and constrain the LBG LF. In Section 3, we present our results and their implication for the evolution of the LBG LF into the reionization epoch, and in Section 4, we discuss the contribution of the detected $z \sim 7$ galaxies to reionization. We adopt the concordance cosmology defined by $\Omega_M = 0.3$, $\Omega_L = 0.7$, $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, that is, $h = 0.7$. Where necessary, we assume $\Omega_bh^2 = 0.02265$ (Hinshaw et al. 2008). Magnitudes are given in the AB system (Oke & Gunn 1983).

### 2. Observations and Source Selection

#### 2.1. The UDF05 and HUDF Data

We reprocessed the HUDF data using improved data reduction algorithms relative to the publicly released data, including an iterative sky subtraction scheme. All NICMOS data were drizzled to a 0.09 pixel scale. The optical ACS data were rebinned to this same scale and convolved with a Gaussian filter to match the width of the NICMOS point-spread function (PSF). We used the $H_{160}$-band data to detect galaxies with the SExtractor program (Bertin & Arnouts 1996), and measured their colors in elliptical apertures scaled to 1.5 times their Kron radii, matched to the detection image. Total magnitudes were measured in 2.5 Kron (AUTO) apertures and were corrected for flux losses in the wings of the PSF (0.07-0.10 mag).

Only detections with a signal-to-noise ratio ($S/N$) larger than 4.5 within $0.3\,''$ radius apertures in the $H_{160}$ band were considered. Flux variations in apertures of different sizes, laid down on empty (sky) areas, were estimated in order to correct for pixel-to-pixel noise correlation in the images; the rms maps were then rescaled so as to match the noise in 0.3 radius apertures. Undetected fluxes were replaced with their 1$\sigma$ upper limits. The zero points of the $J_{110}$ and $H_{160}$ filters were corrected by 0.16 and 0.04 mag, respectively, in order to account for nonlinearity of the NICMOS NIC3 detector (see de Jong 2006). Note that any additional effect of detector nonlinearity would be minimal as our sample covers only a small range in magnitudes.

#### 2.2. The $z_{850}$-Dropout Candidates

Candidate galaxies at redshifts between 6.8 and 8 were selected from the SExtractor catalog according to the following color criteria:

$$(z_{850} - J_{110}) > 1.3,$$

$$(z_{850} - J_{110}) > 1.3 + 0.4(J_{110} - H_{160})$$

$$(J_{110} - H_{160}) < 1.2,$$

$$S/N(H_{160}) > 4.5 \land S/N(J_{110}) > 2,$$ and

$$S/N(V_{606}) > 72 \land S/N(V_{775}) > 2.$$ 

This selection is indicated as a gray-shaded region in the $z - J$ versus $J - H$ color–color diagram of Figure 1. The figure also shows tracks of different galaxy types as a function of redshift. A star-forming galaxy with metallicity 0.2$Z_\odot$ and a stellar age of $10^8$ yr is shown with three solid lines, corresponding to $E(B - V) = 0$, 0.15, and 0.3 mag, respectively (using the extinction law of Calzetti et al. 2000). Such star-forming galaxies enter the selection window at $z \sim 6.8$. Lower-redshift galaxies are shown with dash-dotted lines. The hatched region in the diagram corresponds to the

| Field       | $5\sigma$ | $5\sigma$ | $5\sigma$ | $C_{50\%}$ | Area         |
|-------------|-----------|-----------|-----------|------------|--------------|
| NICP12 deep | 28.4      | 28.4      | 27.8      | 27.8       | 0.4          |
| NICP12 shallow | 28.2    | 27.5      | 27.3      | 27.3       | 0.4          |
| HUDF deep   | 28.6      | 28.2      | 27.5      | 27.5       | 0.7          |
| HUDF shallow | 28.6     | 27.6      | 26.9      | 26.9       | 0.5          |

Notes:

$^a$ Within an aperture of 0.3 radius.

$^b$ 50% completeness limit, as estimated in Section 3.1.

Table 1: Depth and Area of the UDF05 and HUDF NICMOS Observations

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Figure 1. The $z - J$ vs. $J - H$ color–color diagram, on which we highlight the selection criterion for $z > 6.8$ galaxies (gray-shaded area). Evolutionary tracks of star-forming galaxies, obtained with Bruzual & Charlot (2003) models, are shown with solid lines, corresponding to dust obscurations of $E(B - V) = 0$, 0.15, and 0.3. Low-redshift galaxy tracks, up to redshift $z = 4$, are obtained from the galaxy templates of Coleman et al. (1980), and are shown as dash-dotted tracks. Dwarf stars are expected to lie in the hatched region (Knapp et al. 2004; Burrows et al. 2006; Pickles 1998). The filled black circles correspond to the four $z \sim 7$ candidate galaxies identified in our UDF05+HUDF data set.

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

Table 2

| ID       | $\alpha$      | $\delta$      | $H_{160}$ | S/N($H_{160}$) | $J_{110} - H_{160}$ | $z_{580} - J_{110}$ | FWHM  |
|----------|---------------|---------------|-----------|----------------|---------------------|----------------------|-------|
| HUDF-480 | 3:32:38.81    | $-27:47:07.2$ | 26.9 ± 0.1 | 7.2            | 0.3 ± 0.3           | 2.4 ± 0.7            | 0'30  |
| HUDF-708 | 3:32:44.02    | $-27:47:27.3$ | 27.3 ± 0.2 | 6.8            | 0.5 ± 0.3           | >2.4                 | 0'29  |
| NICP34-66| 3:33:08.29    | $-27:52:29.2$ | 26.9 ± 0.1 | 12.5           | 0.7 ± 0.3           | >1.6                 | 0'54  |
| NICP34-80 | 3:33:10.63   | $-27:52:31.0$ | 27.8 ± 0.2 | 4.8            | 0.4 ± 0.4           | >1.8                 | 0'35  |

Note. a This object could be a spurious detection. We have detected it with a 2σ significance in $J_{110}$, and it has not been confirmed by an independent reduction of the same data by R. Bouwens (2008, private communication).

Expected location of cool dwarf stars of type M to L (Knapp et al. 2004; Burrows et al. 2006; Pickles 1998).

Note that the color selection that we have adopted in this study is the so-called “conservative” criterion in Bouwens & Illingworth (2006). Relative to the less-restrictive color window that is used in B08, our selection criterion slightly reduces the effective selection volume by excluding galaxies with redshifts between $z \sim 6.5$ and $z \sim 6.8$; however, it is more robust against low redshift interlopers, and, in particular, it more efficiently excludes a possible contamination by passively evolving $z \sim 1.7$ galaxies with a pronounced 4000 Å break.

All SExtractor sources that satisfy the above color criterion were visually inspected; four $z > 6.8$ LBG candidates were identified after removal of spurious detections (e.g., stellar diffraction spikes, edge artifacts, etc.). These four high-$z$ galaxy candidates are shown as filled black circles in the color–color diagram of Figure 1. Images of these sources are shown in Figure 2; their photometry is listed in Table 2. All four $z$-dropouts are rather faint ($H_{160} \gtrsim 27$) and very compact (they are essentially unresolved at the resolution of the NICMOS images). Two of the candidates lie in the shallow flanking region of the HUDF; the remaining two are located in the shallower area of the NICP34 data. As evident from Figure 1, three out of our four high-$z$ candidates support a relatively small amount of dust, $E(B - V) = 0.15$, while the last one (NICP34-66) is consistent with slightly larger extinction.

Three of our four sources are securely detected in both $J_{110}$ and $H_{160}$. The faintest source (NICP34-80) has an S/N of 4.8 in the 0.3 $H_{160}$ aperture and of only $\sim 2$ in the $J_{110}$ aperture. Thus NICP34-80 is a less secure high-$z$ candidate. With the exclusion of NICP34-80, the remaining three objects are also found in the
independent analysis of B08. One of the $z_{850}$-dropouts in our analysis (HUDF-480) had already been reported in previous works (Bouwens et al. 2004b; Bouwens & Illingworth 2006; Coe et al. 2006), and it has also been detected in Spitzer images (Labbé et al. 2006), with IR colors in very good agreement with a star-forming galaxy at $z \sim 7$. The remaining $z_{850}$-dropouts in our sample are either undetected ($< 2\sigma$; NICP34-66/80) or severely blended (HUDF-708) in the existing, publicly available Spitzer data (from the Infrared Array Camera (IRAC) follow-up of GOODS for the HUDF and from the SIMPLE survey for NICP34$^5$). The magnitude limits for the sources in NICP34 are quite bright and thus do not add any constraint on their photometric redshifts.

2.3. Sources of Sample Contamination

There are five possible sources of contamination to the derived sample of $z \sim 7$ galaxy candidates; these are due to (1) spurious detections, (2) cool dwarf stars, (3) low-redshift galaxies with colors similar to $z \sim 7$ galaxies, (4) high-redshift supernovae (SNe), and (5) photometric scatter of low-redshift galaxies into our selection window. In detail:

1. Except for the faintest of our sources, NICP34-80, all candidates are detected at more than $6\sigma$ in $H_{160}$ and more than $3\sigma$ in $J_{110}$. It is, therefore, very unlikely that these high S/N sources are produced by peaks in the noise. In order to estimate the reality of NICP34-80, which is only detected at $2\sigma$ in $J_{110}$, we repeated our analysis on “negative images,” obtained by multiplying the real images by $-1$ (after masking out all detected sources). One “negative source” is detected with $S/N(H_{160}) > 4.5$, $S/N(J_{110}) > 2$, and a pixel flux distribution similar to NICP34-80. Thus, we conclude that NICP34-80 is likely a spurious detection.

2. Except for NICP34-66, whose profile has a FWHM of 0.54, all sources are unresolved (FWHM $\sim 0.29–0.35$; see Table 2). For comparison, stars are measured to have a FWHM of 0.30–0.39 (also see Thompson et al. 2005). Thus, on the basis of their profiles, we cannot exclude the possibility that our candidates are stars. However, they all show colors redder than expected for ultracool dwarfs. Such stars should have at least weak detections in our ultradeep $z_{850}$ data. Therefore, it is unlikely that our candidates are dwarf stars. However, simulations of dwarf star LFs by Burgasser (2004) predicted that there will be $\sim 0.5$ stars of type L0–T8 in our survey in the magnitude range of $H_{AB} = 27–28$. Thus, this is a non negligible source of contamination.

3. Galaxies at $z \sim 1.2–1.8$, which emit a combination of a red continuum (due to dust or old stellar age) and strong [O III]$\lambda 5007$, $\lambda 4959$ and H$\beta$ emission lines, can exhibit colors that place them within our selection window. The equivalent widths of the emission lines that are required are, however, rather extreme ($\gtrsim 500$ Å rest-frame), which makes this a rather implausible source of contamination.

4. The 2.2 arcmin$^2$ NICMOS observations for the UDF05 data were taken at a much earlier epoch than the corresponding ACS images; high redshift SNe could, therefore, also contaminate our sample. However, with a similar calculation as in B08, we expect to find only 0.03 SNe within the area of our NICMOS observations; this is thus a negligible source of contamination in our sample.

5. Photometric scatter could, in principle, cause some contamination as well. In particular, $z \sim 1.7$ galaxies with prominent 4000 Å breaks, the closest to our selection window, could be a significant source of contamination.

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\textsuperscript{5} http://data.spitzer.caltech.edu/popular/goods/
\textsuperscript{6} http://data.spitzer.caltech.edu/popular/simple/
In order to assess the importance of this effect, we ran simulations in which we applied a suitable photometric scatter to the HUDF source catalog of Coe et al. (2006). This catalog contains sources separately identified both in the optical and in the IR, and includes one of our $z \sim 7$ candidates. The catalog also contains photometric redshifts for all sources. We can thus study the redshift distribution of galaxies, which enter our selection window after applying the photometric scatter. Certainly, this test is limited by the reliabilility of the photometric redshifts. However, it provides a worthy cross-check on our candidates, and we found no low-redshift source in any of the simulation runs. In general, requiring that an object is not detected in any of the optical bands efficiently reduces the contamination from lower-redshift interloper galaxies.

In summary, three of the four detected $z_{850}$-dropouts are very likely to be genuine $z \sim 7$ LBGs. However, we stress that future observations will be needed to confirm these candidates as high-$z$ sources. In the following, we discuss the implications on galaxy formation and reionization upon assuming that these three objects are truly galaxies at $z \sim 7$; we also separately comment on the impact of including the fourth, less likely high-$z$ candidate in our $z \sim 7$ LBG sample.

3. RESULTS

3.1. Expected Versus Detected Number of Sources

In order to estimate the completeness, $C$, and redshift selection probability, $S$, for our sample, we used the procedure that we outlined in Oesch et al. (2007), that is, we simulated data by inserting artificial galaxies into the real images, and ran SExtractor on the simulated data with the same parameters adopted to extract the original catalogs. We adopted colors according to a Gaussian distribution of continuum slopes that is measured for $z \sim 6$ LBGs ($\beta = -2.2 \pm 0.2$; Stanway et al. 2005) and a log-normal size distribution with a size scaling of $(1 + z)^{-1}$ (Ferguson et al. 2004; Bouwens et al. 2004a).

Given a LF, the number of objects expected in a bin of a given magnitude, $\phi$, is given by

$$N(m) = \int dm' \int_{m}^{\infty} dz \frac{dV}{dz} \phi(M(m', z)) S(z, m') C(m'),$$

where $M(m, z) = m - K(z) - DM(z)$ is the absolute magnitude, $M$ the observed magnitude, $K(z)$ the $K$-correction term, and $DM$ the distance modulus. We adopted a $10^8$ yr old, 0.2 $Z_\odot$, star-forming template for the $K$-correction from the observed $H_{160}$ band to rest-frame 2000 Å, with $E(B - V) = 0.15$, consistent with best-fit spectral energy distributions (SEDs) and metallicity estimates of $z \sim 5$ LBGs (e.g., Verma et al. 2007; Ando et al. 2004). Note that correcting to 1400 Å results in a difference of only 0.07 mag. The total number of expected $z \sim 7$ galaxies in our survey is then just the sum over all the fields, which all have different selection probabilities and completeness due to the different depths and data quality.

Assuming no evolution in the LF from $z \sim 6$ to $z \sim 7$, we would expect to detect 12 galaxies in our data set (using the $z \sim 6$ parameters of B07); in contrast, only three, or at most four (if the least reliable candidate, NICP34-80, is also included), are detected. In particular, we would expect about four galaxies brighter than $H_{160} < 26.75$. No such bright candidate is observed, which leads us to conclude, albeit with a limited significance, that there is evolution in the LBG LF from $z \sim 6$ to $z \sim 7$. From Poissonian statistics, the detection of four sources out of the expected 12 has a significance of $2.3\sigma$; when cosmic variance is considered, the significance of the result is reduced down to $1.4\sigma$. The same, that is, a chance of $8\%$, is found from accurate beam tracing through a dark matter simulation in which halos are populated with galaxies, taking into account the specific geometry of our survey (Trenti & Stiavelli 2008).

Note, however, that as commented above, the NICP34-80 source is likely a spurious detection; should this or any other high-$z$ candidate in our sample turn out to be an artifact (or a lower-redshift interloper), this would imply a stronger evolution of the LF over the $z \sim 6$ to $z \sim 7$ period. The above estimates, therefore, provide a lower limit to the real evolution of the LF across the reionization boundary.

3.2. The $z \sim 7$ LBG LF

The approach that we use to constrain the $z \sim 7$ LBG LF from our data is to fix the faint-end slope $\alpha$ and the normalization $\phi_*$, and search for evolution in $M_*$ only; this approach is motivated by the finding that $M_*$ is the only LF parameter that substantially varies over the $z \sim 4$–6 redshift range (B07). We adopt a linear evolution $M_*(z) = M_*(z = 5.9) + \beta_*(1 + z)$ and fit the only free parameter, $\beta_*$, to our four (three) $z \sim 7$ candidates. We use the parameters of B07 to anchor the evolution at redshift 5.9, that is, we adopt $\phi_*(z = 5.9) = 1.4 \times 10^{-3} \text{ Mpc}^{-3} \text{ mag}^{-1}$, $\alpha(z = 5.9) = -1.74$, and $M_*(z = 5.9) = -20.24 \pm 0.19$.

To determine $\beta_*$, we maximize the likelihood

$$\mathcal{L} = \prod_i \mathcal{P}\left[N_{\text{obs}}(m_i), N_{\text{exp}}^{\beta_*}\right],$$

where $\mathcal{P}[x, \lambda]$ is the Poisson distribution with mean $\lambda$ evaluated at $x$, $N_{\text{obs}}(m_i)$ is the observed number of objects in the magnitude bin $m_i$, and $N_{\text{exp}}^{\beta_*}$ is the expected number of objects for a given evolution parameter $\beta_*$. The best fit for $\beta_*$ is $0.36 \pm 0.18$, which translates into $M_*(z = 7.2) = -19.77 \pm 0.30$. If we exclude the faintest, least-reliable $z_{850}$-dropout candidate from the fit, the result changes only slightly, that is, $\beta_* = 0.43 \pm 0.19$ or $M_*(z = 7.2) = -19.68 \pm 0.31$. Within the errors, these values are identical, and we adopt a fiducial value of $M_*(z = 7.2) = -19.7 \pm 0.3$ at 2000 Å. With this evolving LF, the redshift distribution of our sources is predicted to be $z = 6.8$–7.7 (within the 16th and 84th percentiles), with a mean $\overline{z} = 7.2$. The resulting LF is shown in Figure 3 as a dashed line; the figure assumes that all candidates lie at $z \sim 7.2$, with the effective volume estimated as $V_{\text{eff}}(m) = \int_{m}^{\infty} dz \frac{dV}{dz} S(z, m) C(m)$.

Since the measured evolution is mostly driven by the non-detection of bright sources, the effect of varying the faint-end slope $\alpha$ is very small. Varying $\alpha$ by 0.16 (the formal $1\sigma$ error of the $z \sim 6$ LF) changes the value of $M_*(z = 7.2)$ by only $\pm 0.03$ mag. We have also tested how the LF would evolve if $M_*$ does not evolve while $\phi_*$ varies with redshift; this would result in a $\phi_*$ value a factor of $\sim 2.5$ lower than that at $z \sim 6$, that is, $\phi_*(0.56 \pm 0.50) \times 10^{-3}$.

B08 used a large sample of NIR data covering an area of 261 arcmin$^2$ (including the ultradeep NICMOS data of this work) and found $M_* = -19.8$ and $\phi_* = 1.1 \times 10^{-3} \text{ Mpc}^{-3} \text{ mag}^{-1}$, which are in very good agreement with our results (also see Figure 3). Furthermore, Mannucci et al. (2007) searched
the ground-based Very Large Telescope (VLT)/ISAAC J, H, and Ks data on the GOODS field for z850-dropouts and, after removing probable dwarf stars, they found no candidates down to a UV rest-frame absolute magnitude of $M_{1500} = -21.4$. These authors inferred an upper limit on the LF down to this magnitude, which we also report in Figure 3; this upper limit is in good agreement with the extrapolation to brighter magnitudes of our $z \sim 7$ LF.

4. IMPLICATIONS FOR GALAXY EVOLUTION AND REIONIZATION

4.1. Evolution of the SFR Density and Star-Formation Histories of $z \sim 6$ LBGs

From the above LF, we can compute the amount of evolution in the cosmic SFR density from $z \sim 6$ out to $z \sim 7$. Integrating down to $0.2 L_\star (z = 6)$, corresponding to $M = -18.5$, we find a decrease in the luminosity density by 50%, that is, $\log(\rho [\text{erg/s/Hz/Mpc}^3]) = 25.5 \pm 0.2$. Using the relationship between UV continuum and SFR of Kennicutt (1998), this corresponds to a SFR density of $10^{-2.32 \pm 0.23} M_\odot \text{yr}^{-1} \text{Mpc}^{-3}$. Assuming that the LF evolves only in density instead implies a reduction of 60%. Thus, independent of the specific assumption on the LF evolution (either in $M_\star$ or in $\phi_\star$), down to this brightness limit, the luminosity density, and thus the SFR density, drops by a factor of 2–2.5 over the ~170 Myr that separate the $z = 6$ and $z = 7$ epochs. Mannucci et al. (2007) and B08 independently found similar results. Note that the conversion of Kennicutt is applicable for galaxies with continuous star formation over timescales of a few 100 Myrs and Salpeter initial mass function (IMF). They might differ for galaxies that experience stochastic bursts, as is assumed for high-z LBGs (Verma et al. 2007). However, larger differences are expected due to uncertainties in the IMF.

The observed decline of the bright end of the LF from $z \sim 6$ out to $z \sim 7$ provides an upper boundary on the ensemble-average SFR of $z = 6$ LBGs ~170 Myr prior the epoch at which they are observed. Eyles et al. (2007) have investigated the ensemble-average star-formation history of $i_{775}$-dropouts brighter than $z_{850} = 27$ in the GOODS field, and suggested that this rises from $z \sim 6$ to a peak at $z \sim 7.5$ and declines beyond this redshift. Using Bruzual & Charlot (2003) models and assuming the star-formation history of Eyles et al. (2007), we find that the rest-frame 1500 Å luminosity density should show an increase by a factor of ~2.5 from $z \sim 6$ up to 7, that is, in striking contrast with the drop of the luminosity density that we report above. Dust corrections cannot reconcile this disagreement, unless an evolution toward larger dust obscuration at higher redshifts is invoked.

This apparent contradiction could, however, be an artifact of the specific star-formation history that has been adopted by Eyles et al. (2007) in the computation of the ensemble average. Generally, Spitzer data of $i_{775}$-dropouts in the GOODS fields have revealed prominent 4000 Å breaks in a large fraction of these sources (~40%), indicating up to 90% of old stellar populations in those $z \sim 6$ galaxies (Yan et al. 2005; Eyles et al. 2007).
Figure 4. Filling factor of ionized hydrogen as a function of redshift. The solid lines show the evolution of the filling factor calculated by assuming a faint-end slope $\alpha = -1.74$ and an evolution of the galaxy LF by 0.35 mag per unit redshift, and by integrating down to different limiting SFRs ($\sim 1 \times 10^{-2}$, lower gray, black, and upper gray lines, respectively). The dashed line assumes the same evolution in $M_*$ but $\alpha = -1.9$. The dash-dotted line corresponds to no evolution of the LF from $z \sim 6$ out to $z = 20$; the dotted one assumes the same but with the $z \sim 7$ LF. If not stated otherwise, all curves are integrated down to SFRs of $10^{-2} M_\odot$ yr$^{-1}$. The corresponding electron-scattering optical depths are also indicated.

Our results on the $z \sim 7$ LF provide global support to a scenario where a large fraction of stars in the $z \sim 6$ population form at redshifts well above $z \sim 7$.

4.2. Do Galaxies Reionize Our Universe?

Consistent with the decrease in cosmic SFR density, the rate of ionizing photons produced by LBGs must also decrease between $z \sim 6$ and $z \sim 7$.

Bolton & Haehnelt (2007) pointed out that, with the estimated $z \sim 7$ LF of Bouwens et al. (2004b), the number of ionizing photons falls short by almost an order of magnitude to even just keep the universe ionized at $z \sim 7$. Only models in which the SFR rises or stays constant beyond $z \sim 6$ are able to provide enough ionizing photons. This result was, however, derived by including only galaxies with absolute magnitudes brighter than $M = -18$ mag; this corresponds to a lower limit for the SFR of $\sim 1 M_\odot$ yr$^{-1}$ (see the lower gray line in Figure 4). For LF faint-end slopes as steep as those that are measured, however, $\sim 50\%$ of the luminosity density comes from galaxies beyond the current detection limits at $z \sim 6$ ($M > -17$ mag). Thus, photons from these very faint galaxies will add a substantial contribution to the reionizing flux.

Here we adopt the results of our independent analysis of the $z \sim 7$ LF, which, using substantially improved data products, confirms the drop in the SFR density from $z = 6$ to $z = 7$, suggested by Bouwens et al. (2004b). We follow the approach of Bolton & Haehnelt (2007) to estimate the contribution of galaxies to reionization. We include, however, the contribution of faint galaxies to reionization by decreasing the lower limit SFR to $10^{-2} M_\odot$ yr$^{-1}$ in our calculations.

Computations of the filling factor of ionized hydrogen, $Q_{\text{H}II}$, critically depend on the adopted values of the clumping factor $C$ and escape fraction $f_{\text{esc}}$. Scenarios with larger clumping factors lead to more efficient recombinations and thus require more ionizing photons; lower escape fractions also require more photons. Both the clumping factor and the escape fraction are, however, poorly known. To give an upper limit on the potential for reionization of the galaxy population, we adopt (possibly somewhat optimistic) values of $C = 2$, as found in simulations (see discussion in Bolton & Haehnelt 2007), and $f_{\text{esc}} = 20\%$, the upper limit that has been inferred from both observations and simulations (e.g., Shapley et al. 2006; Siana et al. 2007; Gnedin et al. 2008b). We neglect any possible mass dependence of $f_{\text{esc}}$.

Assuming that (1) the constant dimming of $M_*$ with redshift continues beyond $z \gtrsim 7$ and (2) a faint-end slope $\alpha$ that remains constant at the value $\alpha = -1.74$ that is measured at $z \sim 6$ (i.e., our “fiducial” evolution parameters), the galaxy population would be able to ionize the universe only up to a fraction $Q_{\text{H}II} \sim 65\%$ (see solid lines in Figure 4). The corresponding optical depth to electron scattering is $\tau = 0.044$, which is $\sim 2.5\sigma$ lower than the Wilkinson Microwave Anisotropy Probe-5 (WMAP-5) value of $\tau = 0.087 \pm 0.017$ (Dunkley et al. 2008). Thus, this reionization scenario starts too late, ionizing too few atoms at high redshifts. Indeed, the WMAP-5
data suggest that the Universe underwent an extended period of partial reionization, beginning as early as $z \sim 20$, similar to the double reionization scenario proposed by Cen (2003). If by $z \sim 9$, the Universe is already substantially ionized by some other sources, the galaxy population would certainly be able to complete the reionization process by $z \sim 6$.

Another possibility is that the $z > 7$ LF has a faint-end slope that is steeper than is currently observed at $z \sim 6$ (predicted, e.g., by Ryan et al. 2007). The current estimate(s) does not allow one to rule out that the faint end of the LF at such early epochs is as steep as $\alpha = -2$, which would result in a diverging luminosity density. To assess whether the faint galaxy population can provide enough additional photons to complete reionization by $z \sim 6$, we adopt a value of $\alpha = -1.9$ (see the dotted line in Figure 3) and recompute the filling factor assuming no evolution in the neutral hydrogen under these modified assumptions. This scenario is shown in Figure 4 as a dashed line. Such a steep faint-end slope for the LF would result in an end of reionization by $z \sim 6$, and in an integrated electron-scattering optical depth of $\tau = 0.049$, which is still substantially lower than the current WMAP-5 value. For comparison, in Figure 4, we also show the evolution of the H ii filling factor assuming no evolution in the LF from $z \sim 6$ ($z \sim 7$) to $z = 20$. Integrating the luminosity density again to $10^{-2} M_\odot \text{yr}^{-1}$, this results in the completion of reionization by $z \sim 6.6$ ($\sim 5.4$) and in an optical depth $\tau = 0.083$ (0.069).

We therefore conclude that (1) in order for the galaxy population to provide a substantial contribution to reionization, galaxies below current detection limits must play a significant role; (2) under this assumption, a galaxy population that evolves by 0.35 mag per redshift unit would be able to ionize the Universe by $z \sim 6$, provided that the LF faint-end slope is steeper than the $\alpha = -1.74$ value that is measured at redshifts $z \lesssim 6$; (3) even under this assumption, the resulting optical depth to electron scattering is lower by $\sim 2\sigma$ relative to the WMAP-5 measurement, indicating that too few atoms are ionized at very high redshift. This finding provides evidence that if reionization is primarily driven by galaxies, either the currently detected evolution of the galaxy population slows down at $z \gtrsim 7$ or the LF evolution is compensated by a decrease in metallicity and a corresponding increase in ionization efficiency (Stiavelli et al. 2004). Otherwise, other sources like miniquasars or population III stars must substantially participate to reionize our Universe (e.g., Shull & Venkatesan 2008, Madau et al. 2004; Sokasian et al. 2004).

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