THE UDF05 FOLLOW-UP OF THE HUBBLE ULTRA DEEP FIELD. III. THE LUMINOSITY FUNCTION AT z ∼ 6

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ABSTRACT

In this paper, we present a derivation of the rest-frame 1400 Å luminosity function (LF) at redshift six from a new application of the maximum likelihood method by exploring the five deepest Hubble Space Telescope/Advanced Camera for Surveys (HST/ACS) fields, i.e., the Hubble Ultra Deep Field, two UDF05 fields, and two Great Observatories Origins Deep Survey fields. We work on the latest improved data products, which makes our results more robust than those of previous studies. We use unbinned data and thereby make optimal use of the information contained in the data set. We focus on the analysis to a magnitude limit where the completeness is larger than 50% to avoid possibly large errors in the faint end slope that are difficult to quantify. We also take into account scattering in and out of the dropout sample due to photometric errors by defining for each object a probability that it belongs to the dropout sample. We find the best-fit Schechter parameters to the z ∼ 6 LF are α = 1.87 ± 0.14, M* = −20.25 ± 0.23, and φ* = 1.77 +0.62 −0.49 × 10−3 Mpc−3. Such a steep slope suggests that galaxies, especially the faint ones, are possibly the main sources of ionizing photons in the universe at redshift six. We also combine results from all studies at z ∼ 6 to reach an agreement in the 95% confidence level that −20.45 < M* < −20.05 and −1.90 < α < −1.55. The luminosity density has been found not to evolve significantly between z ∼ 6 and z ∼ 5, but considerable evolution is detected from z ∼ 6 to z ∼ 3.

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

Online-only material: color figures

1. INTRODUCTION

Deep imaging surveys, such as the Great Observatories Origins Deep Survey (GOODS; Giavalisco et al. 2004) and the Hubble Ultra Deep Field (HUDF; Beckwith et al. 2006), have been extensively analyzed to study galaxy properties out to the reionization epoch. The rest-frame ultraviolet (UV) galaxy luminosity function (LF) is measured for samples of Lyman break galaxies (LBGs) and used to detect cosmic evolution. The consensus that has developed is that a considerable increase in the space density of galaxies at the bright end of the LF occurs from redshift z ∼ 6 (Bunker et al. 2004; Yan & Windhorst 2004; Beckwith et al. 2006; Bouwens et al. 2006)11 to z ∼ 3 (e.g., Steidel et al. 1999). However, there are still some discrepancies in the interpretation of this evolution in terms of density, slope, luminosity, or a combination of these. Bunker et al. (2004) undertake a photometric analysis of the HUDF i775-dropouts and propose that the density increases sixfold from z ∼ 6 to z ∼ 3, in agreement with Beckwith et al. (2006). Yan & Windhorst (2004) push the detection limit deeper to magnitude 30, finding a steeper faint slope at z ∼ 6 compared to z ∼ 3 by 0.2–0.3. Furthermore, Bouwens et al. (2006) estimate corrections to the measured quantities to account for various observational effects and conclude that the intrinsic luminosity is ∼0.8 mag fainter at z ∼ 6. Their conclusions remain qualitatively unchanged after Reddy & Steidel (2009) recently revisit the LF parameters at z ∼ 3. On the other hand, ground-based observations, e.g., McLure et al. (2009), find an even stronger luminosity evolution.

Different measurements of the luminosity density (LD) or star formation rate also give somewhat different results (e.g., Bunker et al. 2004; Bouwens et al. 2006). It is important to establish whether these observed differences are due to intrinsic differences in the evolution of different galaxy populations or due to issues with the derivation of the LF.

Spectroscopic confirmations of z ∼ 6 galaxies, e.g., Malhotra et al. (2005), Dow-Hygeland et al. (2007), Hathi et al. (2008), and Vanzella et al. (2009), have already proven the effectiveness and robustness of the dropout technique in selecting LBGs. However, the faint LBGs, which are essential to determining the faint-end slope of the LF, have not been spectroscopically confirmed because they require impractically long exposure time on large telescopes.

Based on observations made with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. These observations are associated with program 10632 and 11563.

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11 The results of these groups are summarized in Table 4.
Therefore, to improve upon the previous studies of the $z \sim 6$ LF and to establish its form, a number of difficult issues should be considered. (1) Optimal use of the data: a single field provides us with only a handful of candidates so that some magnitude intervals contain only very few objects. Thus, it is very important to keep all the information. In order to do so, we use unbinned data. (2) Completeness of the catalogs: the magnitude intervals contain only very few objects. Thus, it is important that the recovery simulations are done using the same SExtractor parameters used to derive the catalog. $C(m)dm$ represents the probability that a galaxy at a given magnitude $m$ and at a given observed magnitude $m$ satisfies the selection criteria. Naturally, the product of these two functions is detected with magnitude $m$ AND selected as an LBG.

We adopt $\Lambda$CDM cosmology: $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$. Magnitudes are in the AB system.

### Table 1

| HUDF | GOODS-S | GOODS-N | NICP12 | NICP34 |
|------|---------|---------|--------|--------|
| $N_{\text{tot}}^a$ | 115 | 373 | 502 | 120 | 54 |
| $N_i^b$ | 58.1 ± 2.3 | 103.1 ± 6.5 | 116.2 ± 7.0 | 33.9 ± 3.0 | 23.5 ± 5.7 |

**Notes.**

*$^a$ Total number of galaxies in our candidates pool.

*$^b$ Average number of galaxies in one realization.

#### 3. Luminosity Function of LBGs at $z \sim 6$

The completeness function $C(m)(m)$ is the apparent/detected magnitude and the selection function $S(m, z)(z)$ is the redshift) are measured by performing recovery simulations in the same way as in Paper II, i.e., by inserting artificial galaxies into our science images and rerunning SExtractor with the same setup as for the original catalog generation. We use a $\beta$-distribution $-2.2 \pm 0.4$ (Stanway et al. 2005) and a size distribution following a scaling of $(1+z)^{-1}$ as in Ferguson et al. (2004). For each redshift bin $\delta z = 0.1$, we thus compute the color a galaxy would have with the randomly chosen $\beta$-value and insert it in the images. The input magnitudes are following a flat distribution from 24 to 29, but the selection function is given at observed magnitudes, simply by computing the fraction of galaxies that we insert with the measured output magnitude which is selected by the $i_{775}$-dropout criteria. $C(m)dm$ is defined as the probability that a galaxy of $m$ in the images is selected in the catalog, which depends strongly on SExtractor parameters such as DEBLEND. Thus, it is important that the recovery simulations are done using the same SExtractor parameters used to derive the catalog. $S(m, z)dm$ represents the probability that an LBG at a given redshift $z$ and at a given observed magnitude $m$ satisfies the selection criteria. Naturally, the product of these two functions $C(m)S(m, z)dm$ is the probability that a galaxy at redshift $z$ is detected with magnitude $m$ AND selected as an LBG.

The UV LF can be expressed in the Schechter form as

$$\phi(M) = (0.4 \ln 10)\phi_0 10^{0.4(M_m - M)} \exp[-10^{0.4(M_m - M)}]$$

with the absolute magnitude $M = m - DM(z) - K_c(z)$, where $DM(z)$ is the distance modulus and $K_c(z)$ is the $K$-correction from observed $z_{850}$ to rest frame 1400 Å.

Binned data were initially utilized by many groups to derive the shape of the LF. The observed number of LBGs within the apparent magnitude bin $m_l < m < m_u$ is predicted as

$$N_i = \int dz \frac{dV_C}{dz} \int_{m_l}^{m_u} dm C(m)S(m, z)\phi(M(m, z); \phi_0, M_m, \alpha),$$

where $dV_C/dz$ is the comoving volume element of the source. Binning may lose information and lead to biased results dependent on the bin size. At the same time, having very few luminous candidates in current high-$z$ surveys, there is uncertainty about the numbers in the bright bins since the candidates could jump into adjacent bins due to photometric errors. Simulations by Trenti & Stiavelli (2008) show that binning is likely to affect the confidence regions for the best-fitting parameters.
To overcome these drawbacks, in this section we present an improved approach based on the ML method (Fisher 1922; Sandage et al. 1979, STY) to make optimal use of every possible LBG in the fields. As also pointed out by Trenti & Stiavelli (2008), the STY ML estimator relies essentially on unbinned data. We determine the shape of the LF by exploring every single detected dropout. First, we find the probability for each galaxy that it could be selected as an LBG, considering the photometric uncertainty of the catalogs (Section 3.2). Second, we choose galaxies randomly by the above probability and run our ML process (Section 3.3). Third, we repeat the above step enough times to achieve convergence.

### 3.1. Selection Criteria

We adopt the $i_{775}$-dropout selection criteria from Paper I, i.e.,

$$i_{775} - z_{850} > 1.3,$$  \hspace{1cm} (3)

$$S/N(z_{850}) > 5,$$  \hspace{1cm} (4)

and

$$S/N(V_{606}) < 2 \text{ or } V_{606} - z_{850} > 2.8.$$  \hspace{1cm} (5)

The dominant criterion, i.e., the SExtractor MAG_ISO color $i_{775} - z_{850} > 1.3$, will be discussed further in Section 3.2. The signal-to-noise ratio $S/N(z_{850}) > 5$ is demanded for each candidate to largely avoid interlopers (later this subsection) or slope steepening (the Appendix) and to be consistent in comparing with $z \sim 3$ results from Steidel et al. (1999) and with $z \sim 5$ results in Paper II. The photometric errors also take into account the correlated errors present in the images as discussed in Paper II. In addition, we require for CLASS_STAR $< 0.75$ if the MAG_AUTO magnitude $z_{850} < 28.0$ for the HUDF, $< 27.5$ for the UDF05, and $< 26.5$ for the GOODS in order to remove stellar contamination at the bright end (e.g., Bouwens et al. 2006, and Paper II). Only galaxies with $C(m) > 0.5$ have been included to avoid large uncertainty corrections (Table 2).

The selection has been proven to be very efficient and effective. All the spectroscopically confirmed $i_{775}$-dropouts as derived assuming synthetic SEDs and a non-evolving LF in the redshift window $5.7 < z < 7$. The total interloper fraction is estimated to be 24% and is primarily contributed by lower redshift galaxies selected as LBGs due to the aliasing between the Lyman break and the 4000 Å break. The model is pessimistic and at the relatively bright end ($z_{850} < 27.5$) comparison with Malhotra et al. (2005) shows a factor of two fewer interlopers than predicted by the model.

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### 3.2. $f$-factor

Photometric scatter introduces large uncertainties in numbers and magnitudes of the LBG candidates and, therefore, in determined properties of the LF. If a strict color cut such as $i_{775} - z_{850} > 1.3$ was applied, the impact of photometric errors would not be fully explored, and many real LBGs with a little bluer measured color may be missed due to photometric errors. A relaxed cut, e.g., $i_{775} - z_{850} > 0.9$, on the other hand, suffers from larger contaminations. For example, Malhotra et al. (2005) found five objects at intermediate redshifts and four intrinsic $z \sim 6$ galaxies within $0.9 < i_{775} - z_{850} < 1.3$, which means the

| z_{850} | HUDF | NICP12 | NICP34 | GOODS |
|---|---|---|---|---|
| 24.25 | 0.95 | 0.95 | 0.96 | 0.96 |
| 24.75 | 0.94 | 0.94 | 0.95 | 0.96 |
| 25.25 | 0.93 | 0.94 | 0.94 | 0.95 |
| 25.75 | 0.92 | 0.93 | 0.93 | 0.94 |
| 26.25 | 0.91 | 0.92 | 0.92 | 0.86 |
| 26.75 | 0.89 | 0.91 | 0.87 | 0.61 |
| 27.25 | 0.87 | 0.86 | 0.70 | 0.30 |
| 27.75 | 0.79 | 0.72 | 0.43 | 0.10 |
| 28.25^b | 0.60 | 0.47 | 0.19 | ... |
| 28.75 | 0.37 | 0.23 | 0.07 | ... |

Notes.

- ^a Central bin magnitude.
- ^b Only data with completeness above half are considered to avoid large uncertainty corrections.

![Figure 1](image-url) Predicted redshift distribution for $i_{775}$-dropouts as derived assuming synthetic SEDs and a non-evolving LF in the redshift window $5.7 < z < 7$. The total interloper fraction is estimated to be 24% and is primarily contributed by lower redshift galaxies selected as LBGs due to the aliasing between the Lyman break and the 4000 Å break. The model is pessimistic and at the relatively bright end ($z_{850} < 27.5$) comparison with Malhotra et al. (2005) shows a factor of two fewer interlopers than predicted by the model.
that a galaxy is of magnitude $m$ repeatedly to see how often the integration of $i_{775} - z_{850} > 1.3$ LBG candidates is defined as

$$f = \int dz_{850} i_{775} p(z_{850}) p(i_{775}),$$

where the integration of $i_{775}$ is taken over $i_{775} - z_{850} > 1.3$. The real magnitude $m$ is assumed to be a Gaussian distribution around its cataloged magnitude $m_{c}$ (see the Appendix for details). In practice, one could find the values of $f$-factor with a Monte Carlo method by simply generating Gaussian distributed magnitudes repeatedly to see how often the $i_{775} - z_{850} > 1.3$ color would be satisfied. A $2\sigma$ magnitude limit is adopted if there is no detection in the $i_{775}$ band.

It is easy to see that $f > 0.5$ when the cataloged $i_{775} - z_{850} > 1.3$ while $f < 0.5$ when the cataloged $i_{775} - z_{850} < 1.3$, and $f = 0.01$ corresponds to the cataloged $i_{775} - z_{850} < 0.9$ when the $z_{850}$ and $i_{775}$ errors are both 0.2. All $f \geq 0.01$ galaxies are used in the subsequent ML analysis, i.e., have a 1% chance of being included in one realization. Table 1 shows that essentially about 25%–50% candidates in each field will participate in one realization, which brings our sample into agreement with other groups within the magnitude window in study, such as Bouwens et al. (2007). (See Figure 3 and Table 3.)

### 3.3. V-matrix

Due to the unique long tail of the ACS $z_{850}$ filter, the $K$-correction can be as large as 2.2 mag at $z = 5.7$ and goes down to 0.3 mag at $z = 7.0$. Thus, with distance modulus varying by 0.5 mag there could be a 2.4 mag scatter in UV rest-frame absolute magnitudes in realizations at $5.7 < z < 7$ for any given observed $z_{850}$ magnitude. In other words, the relation between $M$ and $m$ is very uncertain. Therefore, where $M$ is relatively insensitive to redshift or the redshift span is relatively small, the effective volume $V_{\text{eff}}$ technique does not fit in our case. This forces us to seek a new formalism.

We define the apparent LF as

$$\Phi(m) = \frac{C(m)}{V_{\text{eff}}} \int dz S(m, z) \frac{dV_C}{dz}(z) \phi(M; m, z),$$

and it does not need to be of Schechter form. The $V$-matrix is therefore

$$V(m, z) = C(m) S(m, z) \frac{dV_C}{dz}(z)$$

and the integrations are always taken over the region of interest, for example for the HUDF, $5.7 < z < 7.0$ and $24.0 < m < 28.5$. (The bright limit is introduced for calculations only when there is no candidate detected beyond this magnitude, and an even brighter limit will not affect the results since the LF is greatly suppressed at this end.) $C(m)$ has been included in the calculation of $V(m, z)$ so that there is no additional completeness correction factor in $p(m)$.\footnote{We note that Marshall (1985) adopted a similar approach to ours and he did not have to take the integration of redshift as shown above since the redshifts of their objects were already known.}
When combining different fields, e.g., the GOODS and the HUDF, no additional rescaling factor is needed in the ML method (Trenti & Stiavelli 2008). The inputs to the ML process are the V-matrix and the magnitudes m of selected candidates. In each realization, candidates are selected from the pool in a probability as to their f-factor. The outputs are $M_\*\alpha$ in as many as possible realizations, when the averages and errors have been convergent. The uncertainty of $m$ considered in the ML process only yields minor errors when several hundreds of galaxies are surveyed (see the Appendix). $\phi_*$ is determined by a $\chi^2$ fit to the observed LBG densities with respect to the 1σ two-parameter contour of $M_\*$ and $\alpha$.

The LF parameters we derive for $z \sim 6$ are: $\alpha = -1.87 \pm 0.14$, $M_\* = -20.25 \pm 0.23$, and $\phi_* = 1.77^{+0.62}_{-0.49} \times 10^{-3}$ Mpc$^{-3}$, as illustrated in Figure 4. We notice our faint end slope $\alpha$ is slightly steeper than that from some other studies.

Since we are investigating a relatively large redshift range $5.7 < z < 7.0$ and finding indications of LF evolution, it is a good sanity check for us to explicitly consider the effect of evolving LF parameters. Assuming $M_\*$ and $\alpha$ are uniform in this redshift range, we assign a linear evolution of $\phi_*(z) = \phi_* (z=6.3) [1-\frac{z-6.3}{3}]$ and repeat the analysis described in Sections 3.1–3.3. We find that $\alpha = -1.92 \pm 0.13$, $M_\* = -20.22 \pm 0.21$. The closeness to our derived parameters for no evolution, i.e., $\alpha = -1.87 \pm 0.14$ and $M_\* = -20.25 \pm 0.23$, shows that our results are robust with respect to an evolution of the LF normalization within the redshift range of $i_{775}$-dropouts.

4. COMPARISON TO OTHER RESULTS

We have verified the internal consistency and robustness of our results and we are now ready to compare them to other studies.

4.1. Most Probable $z \sim 6$ LF

To deal with the weighted average of results from different groups, we follow Press (1996). The probability of getting observed variable(s) $H_0$ from data or measurements $D$ is

$$P(H_0|D) \propto \prod_i \left( P_{Gi} + P_{Bi} \right).$$

Here

$$P_{Gi} \sim \frac{1}{\sigma_i} \exp \left[ \frac{-(H_i - H_0)^2}{2\sigma_i^2} \right]$$

and

$$P_{Bi} \sim \frac{1}{S} \exp \left[ \frac{-(H_i - H_0)^2}{2S^2} \right]$$

are the probability distributions of “good” and “bad” measurements, respectively, where $i$ denotes different measurements, and $S$ should be assigned to be large enough to ensure that measurements do not conflict with each other. When extending this method to two-dimensional analysis, we also consider the correlation between $M_\*$ and $\alpha$ (Figure 4). Press (1996) puts almost no weight on those measurements without errors where $P_{Gi} = 0$ and $P_{Bi}$ is widespread. Instead, we assume a moderate error of 0.3 for those six groups, i.e., Bouwens et al. (2004), Bunker et al. (2004), Dickinson et al. (2004), Yan & Windhorst (2004), Malhotra et al. (2005), and Paper I. Combined with the other four measurements providing errors, i.e., Bouwens et al. (2006, 2007), McLure et al. (2009), and this work, we find there is about a 95% chance that $-20.45 < M_\* < -20.05$ and $-1.90 < \alpha < -1.55$, assuming all the current studies are independent and correct. (See Table 4 and Figure 5.)

4.2. $z \sim 5$ LBGs LF Revisited

In order to further test the method used here, we derive the faint end slope of the $z \sim 5$ LBG LF using the same catalogs and the same selection criteria as those in Paper II. To study the

![Figure 4](https://example.com/figure4.png)

**Figure 4.** Likelihood contour for the best-fit Schechter parameters of the $z \sim 6$ LF. The contours, inner to outer, stand for one-parameter 1σ, two-parameter 1σ, and one-parameter 2σ likelihood contours averaged over realizations for use in the ML process.

![Figure 5](https://example.com/figure5.png)

**Figure 5.** Most probable parameter space at $z \sim 6$ based on 10 studies. The inner contour includes 68% probability and the outer 95%, assuming all the studies are independent and correct. Two nearby squares are from Bouwens et al. (2006, 2007), a third square is from McLure et al. (2009) who combine their data with Bouwens et al. (2007), and the diamond is from this work. As illustrated in Figure 4, $M_\*$ and $\alpha$ are strongly correlated so we do not plot their error bars, which can be found in Table 4.
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Table 4

| References                  | Fieldsa | Nb | α    | Mc |
|-----------------------------|---------|----|------|-----|
| Bouwens et al. (2004)       | UDF Ps (28.1) | 30 | ⋯ 1.15 | −20.26 |
| Bunker et al. (2004)        | HUDF (28.5) | 54 | ≤−1.60 | −20.87 |
| Dickinson et al. (2004)     | GOODS (26.0) | 5 | −1.60 (fixed) | −19.87 |
| Van & Windhorst (2004)      | HUDF (30.0) | 108 | (−1.90, −1.80)c | −21.03 |
| Malhotra et al. (2005)      | HUDF (27.5) | 234 | −1.80 (fixed) | −20.83 |
| Paper I                     | HUDF (29.0) | 54 | −1.60 (fixed) | −20.5 |
| Bouwens et al. (2006)       | HUDF (29.2), d | 506 | −1.73 ± 0.21 | −20.25 ± 0.20 |
| Bouwens et al. (2007)       | HUDF (29.3), e | 627 | −1.74 ± 0.16 | −20.24 ± 0.19 |
| McLure et al. (2009)        | UDS (26.0) | 157d | −1.71 ± 0.11 | −20.04 ± 0.12 |
| This work                   | HUDF (28.5), f | 1164 | −1.87 ± 0.14 | −20.25 ± 0.23 |

Notes.

a The fields and z850-band detection limit studied by the reference.

b The number of candidates.

c −1.9 < α < −1.8.

d All spectroscopically confirmed.

e HUDF (29.2)+HUDF-Ps (28.5)+GOODS (27.5).

(4) | Reddy & Steidel (2009) | Paper II | This Work |
| (z ∼ 3) | (z ∼ 5) | (z ∼ 6) |
|---|---|---|
| Mφ | −20.97 ± 0.14 | −20.78 ± 0.21 | −20.25 ± 0.23 |
| α | −1.73 ± 0.13 | −1.54 ± 0.10 | −1.87 ± 0.14 |
| φb | 1.71 ± 0.53 | 0.90+0.3−0.5 | 1.77±0.62 |
| Lφ | 1.06±0.15 | 0.89±0.19 | 0.55±0.13 |
| LD0.3d | 1.49±0.40 | 0.57±0.14 | 0.46±0.17 |
| LD0.3 | 1.89±0.44 | 0.71±0.15 | 0.68±0.16 |
| LD0.04 | 3.27±0.45 | 1.12±0.15 | 1.70±0.25 |

Notes.

a See Figure 7 for the graph.

b In units of 10−23 Mpc−3.

c In units of 1039 erg s−1 Hz−1.

d In units of 1049 erg s−1 Hz−1 Mpc−3. LD0.3 means that the LD is integrated from 0.3L∗(z = 3)/Lφ(z).

HUDF and NICP12 data that lack enough bright candidates to determine Mφ, we fix Mφ = −20.7 to find α = −1.72 ± 0.04, which is in agreement with the previous results (their Table 3). Thus, our method, designed to deal with the varying K-correction in z850 and to account for additional uncertainties, is equivalent to our previous method in the simpler V606-dropout case.

4.3. z ∼ 6 Luminosity Density

The LD at redshift z equals ∫ Lφ(L)dL = Lφ(z)φ(z) ∫ ∞ 0 x1+αe−xdx, where x = L/Lφ(z). We find there is considerable evolution between z ∼ 6 and z ∼ 3, as shown in Figure 6 for the LF of the same redshift window, but no statistically significant evolution between z ∼ 6 and z ∼ 5. More details are in Table 5 and Figure 7 where x0 = aLφ(z)/Lφ(z) and a = 0.3, 0.2, and 0.04. At lower redshifts there are fewer recombinations in the diffuse medium and therefore the required flux density to keep the universe ionized increases with increasing redshift. If the universe has finished reionizing at z ∼ 6, then it will be kept ionized at z ∼ 5 since the required LD at z ∼ 5 is less than that at z ∼ 6 and the observed ones are close to each other.
5. CONCLUSIONS

In this paper, we have reported the results of a study of a large sample of faint LBGs in the redshift interval $5.7 < z < 7.0$. Working on the five deepest HST fields with their most updated data, we account for the effect of photometric errors by introducing the factor $f$ as the probability that each galaxy is an LBG. We employ unbinned data to keep all the information and to avoid bias, and we develop a modified ML process to reduce the effect of the uncertain relation between $M$ and $m$. Our best-fitting Schechter function parameters of the rest-frame 1400 Å LF at redshift $z \sim 6$ are: $\alpha = -1.87 \pm 0.14$, $M_\ast = -20.25 \pm 0.23$, and $\phi_\ast = 1.77^{+0.62}_{-0.49} \times 10^{-3}$ Mpc$^{-3}$, which suggest evolution of $M_\ast$, possible steepening of $\alpha$, and no change of $\phi_\ast$ compared to their values at $z \sim 3$. Such a steep slope suggests that galaxies, especially the faint ones, are possibly the main sources of ionizing photons in the universe at redshift six (Stiavelli et al. 2004). Combining 10 previous studies at $z \sim 6$ with the extended Press method, we find that the most probable LF favors $-20.45 < M_\ast < -20.05$ and $-1.90 < \alpha < -1.55$ at the 95% confidence level. The LD has been found not to evolve significantly between $z \sim 6$ and $z \sim 5$, but considerable change is detected from $z \sim 6$ to $z \sim 3$.

If $\alpha$ remains constant from $z \sim 6$ to $z \sim 3$ as stated by e.g., Bouwens et al. (2007) and Reddy & Steidel (2009), it will be difficult to tell the intrinsically evolving parameter, $M_\ast$ or $\phi_\ast$, from faint LBGs only, while too few bright LBGs are found due to the limited area of current deep surveys. Ground-based surveys such as the Subaru Deep Field (Shimasaku et al. 2005; McLure et al. 2009) are extremely efficient in detecting bright surveys such as the Subaru Deep Field (Shimasaku et al. 2005; McLure et al. 2009) are extremely efficient in detecting bright LBGs in a large field of view and might clarify whether $M_\ast$ or $\phi_\ast$ alone are not responsible for the change of LF; while splitting the $z_{50}$ band into two separate bands may be useful to isolate the effect of a possible slope steepening (Shimasaku et al. 2005).

We look forward to including IR data from WFC3 on board HST to improve the selection of $z \sim 6$ LBG candidates, and the bright end of the LF will be better determined when the data from CANDELS/ERS (e.g., Bouwens et al. 2010b) and the Brightest of Reionizing Galaxies survey (Trenti et al. 2011) are becoming available.

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APPENDIX

MORE ABOUT PHOTOMETRIC SCATTER AND FLUX BOOSTING

We assume the photometric scatter is in a Gaussian distribution, thus the probability of a galaxy arriving on the detector as magnitude $m$ but cataloged in $m'$ equals

$$G(m, m', \sigma) = \frac{1}{\sqrt{2\pi} \sigma} \exp \left[ -\frac{(m - m')^2}{2\sigma^2} \right]$$  \tag{A1}

and the measured LF will be

$$\phi'(m) = \int \phi(m')G(m, m', \sigma)dm',$$  \tag{A2}

where $\phi$ is the actual LF, i.e., Equation (7) in Section 3.3.

When the photometric error $\sigma$ is very small, $G$ takes the limit of the Dirac function and it is always true, $\phi' \equiv \phi$. When the surveys are pushed close to the detection limit, $\sigma$ is not negligible and also far from uniform in the magnitude window. To satisfy $S/N = 10$ at $m = m_\ast$ and $S/N = 5$ at $m = m_\ast + 2.5$, a guess would be

$$\sigma(m) = \frac{2.5}{\ln 10} \frac{1}{(m_\ast - m) + 10}.$$  \tag{A3}

Simulations show that the effect of flux boosting from fainter magnitudes outside our selection window is negligible. But as shown in Table 6, if $\sigma(m)$ increases much faster with $m$, or if lower S/N candidates are included, there will be considerable steepening at the faint end due to the photometric scattering. We simulate 4000 objects according to the given LF parameters, i.e., $m_\ast$ is fixed and $\alpha = -1.7$ in $[m_\ast - 3.5, m_\ast + 4.5]$. Their magnitude errors are assumed to be in the form of $10^{1.5(m-m_\ast)}$, which comes from the real data of the HUDF. For each realization, the change of magnitudes brought by their errors will also change their detected $S/N$. We choose those with $S/N > 5$ and lying within $[m_\ast - 2.5, m_\ast + 2.5]$ to determine the slope. This process repeats for different combinations of $S/N > 5$, 7, 9 and $\alpha = -1.5, -1.7, -1.9$. We can see from Table 6 that if the S/N is kept $> 5$, the steepening of the faint end slope by the flux boosting is less than 0.1.

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