

KECK SPECTROSCOPY OF LYMAN-BREAK GALAXIES AND ITS IMPLICATIONS FOR THE UV-CONTINUUM AND LY α LUMINOSITY FUNCTIONS AT $z > 6$

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ABSTRACT

We present Keck spectroscopic observations of $z > 6$ Lyman-break galaxy (LBG) candidates in the Subaru Deep Field (SDF). The candidates were selected as i' -dropout objects down to $z' = 27$ AB magnitudes from an ultra-deep SDF z' -band image. With the Keck spectroscopy we identified 19 LBGs with prominent Ly α emission lines at $6 \leq z \leq 6.4$. The median value of the Ly α rest-frame equivalent widths (EWs) is ~ 50 Å, with four EWs > 100 Å. This well-defined spectroscopic sample spans a UV-continuum luminosity range of $-21.8 \leq M_{UV} \leq -19.5$ ($0.6 \sim 5 L_{UV}^*$) and a Ly α luminosity range of $(0.3 \sim 3) \times 10^{43}$ erg s⁻¹ ($0.3 \sim 3 L_{Ly\alpha}^*$). We derive the UV and Ly α luminosity functions (LFs) from our sample at $\langle z \rangle \sim 6.2$ after we correct for sample incompleteness. We find that our measurement of the UV LF is consistent with the results of previous studies based on photometric LBG samples at $5 < z < 7$. Our Ly α LF is also generally in agreement with the results of Ly α -emitter surveys at $z \sim 5.7$ and 6.6 . This study shows that deep spectroscopic observations of LBGs can provide unique constraints on both the UV and Ly α LFs at $z > 6$.

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

1. INTRODUCTION

The last decade saw great progress in our understanding of the distant Universe as a number of objects at $z > 6$ were discovered, including galaxies (Iye et al. 2006; Vanzella et al. 2011), quasars (Fan et al. 2003; Willott et al. 2010), and γ -ray bursts (Haislip et al. 2006; Tanvir et al. 2009). They provide key information to study the formation and evolution of the earliest galaxies, supermassive black holes, and massive stars when the Universe was less than one billion years old. The observations of these objects such as the detection of Gunn-Peterson troughs in quasar spectra (Fan et al. 2006), together with the measurements of the polarization anisotropies in the cosmic microwave background (Komatsu et al. 2009), indicate that at $z > 6$ we are approaching the epoch of cosmic reionization, during which the intergalactic space became transparent to HI-ionizing UV photons.

The first $z > 6$ galaxies were discovered to be Ly α emitters (LAEs) at $z \sim 6.56$ using the narrow-band technique (Hu et al. 2002; Kodaira et al. 2003). This technique has been an efficient way to find high-redshift galaxies since the work of Cowie & Hu (1998)

and Rhoads et al. (2000). The number of $z > 6$ LAEs has increased to almost one hundred with a high success rate of spectroscopic confirmation due to the presence of strong Ly α emission lines (Taniguchi et al. 2005; Iye et al. 2006; Kashikawa et al. 2006; Hu et al. 2010; Ota et al. 2010; Ouchi et al. 2010; Cassata et al. 2011; Kashikawa et al. 2011). Now Ly α surveys are able to detect LAE candidates at $z = 7.7$ (Hibon et al. 2010; Tilvi et al. 2010). However, the narrow-band technique has its own limitations. Narrow-band filters are built to use dark atmospheric windows with little sky OH emission. Such windows are rare at the red end of the optical range (even rarer in the near-IR), and are also very narrow (~ 100 Å), resulting in small survey volumes. The dropout technique (Steidel & Hamilton 1993; Giavalisco 2002) does not have these limitations. It has produced a substantial number of Lyman-break galaxy (LBG) candidates at $z > 6$ (Bunker et al. 2004; Dickinson et al. 2004; Yan & Windhorst 2004; Bouwens et al. 2008). Most recently with the power of the new *HST* WFC3/IR camera, LBG candidates at $z > 7$ (up to $z \sim 10$) are being routinely found (Bunker et al. 2010; Finkelstein et al. 2010; Oesch et al. 2010; Wilkins et al. 2010; Yan et al. 2010; Bouwens et al. 2011; Lorenzoni et al. 2011, and references therein), although they are mostly too faint to be spectroscopically confirmed by current facilities.

With the large sample of LBG candidates, the galaxy UV luminosity function (LF) at $z > 6$ has been established. The general result is that the faint-end slope of the LF at $z \sim 6$ is very steep, and the characteristic luminosity dims significantly from lower redshifts to $z \sim 6$ (Bouwens et al. 2007; McLure et al. 2009). Now one of the main concerns is that there is a lack of well-defined spectroscopic LBG samples to cross-check the LF. As mentioned above, spectroscopic identifications of $z > 6$ LBG candidates are extremely difficult unless they are bright and have strong Ly α emission lines, in

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which case spectroscopy could still be costly (Stark et al. 2010; Ono et al. 2011; Vanzella et al. 2011). Unfortunately most of the known LBG candidates at $z > 6$ are in the Hubble Ultra Deep Field (HUDF) due to the abundance of the high-quality deep data, and thus they are very faint. Even the *HST* WFC3 early release science data (Windhorst et al. 2011) cover only $40\text{--}50\text{ arcmin}^2$ and bright candidates are rare. With a great depth over an effective area of $\sim 876\text{ arcmin}^2$, the Subaru Deep Field (SDF; Kashikawa et al. 2004) provides a unique field to search for relatively bright LBGs.

The SDF project has been very successful in searching for high-redshift galaxies. Taking advantage of an 8-m telescope and a prime-focus camera with a large field-of-view (FOV, $34' \times 27'$), SDF has an impressive depth ($27.5 \sim 28.5\text{ AB mag}$) in five broad bands $BVRi'z'$ over a survey area of one FOV. Especially noteworthy is the deep observations with three narrow-band filters, NB816, NB921, and NB973, corresponding to the detection of LAEs at $z \sim 5.7$, 6.5 , and 7 , respectively. So far SDF has spectroscopically identified ~ 100 LAEs at $z \sim 5.7$ (e.g. Shimasaku et al. 2006) and $z \sim 6.5$ (e.g. Kashikawa et al. 2006, 2011), and a few LAEs at $z \sim 7$ (Iye et al. 2006; Ota et al. 2010). SDF has also found a sample of bright LBG candidates at $z > 6$ (Shimasaku et al. 2005) up to $z > 7$ (Ouchi et al. 2009). Five strong LAEs from a list of i' -dropout objects (or LBG candidates) have already been spectroscopically confirmed at $6 < z < 6.4$ (Nagao et al. 2004, 2005, 2007). Note that the difference between LAEs and LBGs is somewhat arbitrary and there is no clear separation line between them, so we simply call the galaxies found by the narrow-band technique as LAEs and those found by the dropout technique as LBGs. A LBG is also a LAE if it is identified to have a strong $\text{Ly}\alpha$ emission line.

In this paper we present our deep spectroscopic observations of $z > 6$ LBG candidates in SDF using a new, ultra deep z' -band image (29 hour integration) for target selection. This image allows us to select candidates down to $z' = 27\text{ mag}$, roughly one mag deeper than the LBGs found by Nagao et al. (2004, 2005, 2007). The structure of the paper is as follows. Section 2 briefly describes our selection criteria and follow-up observations of galaxy candidates. Section 3 presents the results of our spectroscopic observations. We derive the UV-continuum and $\text{Ly}\alpha$ LFs in Section 4, and summarize the paper in Section 5. Throughout the paper we use a Λ -dominated flat cosmology with $H_0 = 70\text{ km s}^{-1}\text{ Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$. All magnitudes are on an AB system (Oke & Gunn 1983).

2. OBSERVATIONS AND DATA REDUCTION

2.1. Selection of Galaxy Candidates at $z > 6$

We selected $z > 6$ galaxy candidates using the SDF broad-band images. The SDF public data have a depth of $B = 28.45$, $V = 27.74$, $R = 27.80$, $i' = 27.43$, $\text{NB921} = 26.54$, and $z' = 26.62$ (3σ detection for point sources), covering an effective area of $\sim 876\text{ arcmin}^2$. Nagao et al. (2004, 2005, 2007) have used the public data to find bright LBGs down to $z' \sim 26.1$. Recently the SDF team has obtained a much deeper z' -band image with a total integration time of ~ 29 hours and a depth of $\sim 27.5\text{ mag}$ (Poznanski et al. 2007; Richmond et al.

2009). Our candidate selection was based on this deep z' -band image together with the public data in the other four bluer broad bands.

We used the traditional dropout technique, i.e., our candidates are i' -band dropout objects. The basic criteria are

$$z' < 27 \text{ and } i' - z' > 1.7. \quad (1)$$

The color cut is more stringent than $i' - z' > 1.5$ used by Nagao et al. (2004, 2005, 2007). This is to reduce the number of contaminants scattered into the selection region due to large i' -band photometric errors. To remove foreground contaminants, we required that the candidates are not detected ($< 2\sigma$) in three broad bands BVR . We also rejected possible $z \sim 6.56$ LAE candidates which are relatively bright in the NB921 band with respect to their z -band photometry ($z' - \text{NB921} < 1$), since these candidates were being targeted in another program (Kashikawa et al. 2011). We obtained 499 i' -dropouts in the whole SDF field. We then visually inspected each candidate, and removed those with any possible detections in any of the BVR bands and those that were likely spurious detections (e.g. blended with bright stars). The i' -band image is deep enough in most cases of our selection. In the extreme case of $z' = 27$ in which the color cut determines $i' > 28.7$, we visually inspected the candidates and simply required that the candidates should not be detected in the i' -band (in addition to the BVR bands). We generated an $i' = 28.7$ point source (almost all known $z \geq 6$ SDF galaxies are point sources in SDF images) and put it in a number of blank regions of the i' -band image. We cut out these regions and mixed them with other blank regions that do not have the simulated point source. As a result, more than 95% of the regions with the $i' = 28.7$ source were visually identified, so our visual inspection is reliable in this case. Finally, 196 promising candidates survived for our follow-up spectroscopy.

2.2. Keck/DEIMOS Spectroscopy

The follow-up spectroscopic observations were carried out with DEIMOS (Faber et al. 2003) on the Keck II telescope on 25–28 April 2009. The typical seeing was $1''$. A total of 79 galaxy candidates from the above were covered by six masks, but only 73 of them were observed due to slit conflict. There were roughly 100 slitlets per mask; most of the slitlets were assigned to the targets of Kashikawa et al. (2011) and various secondary targets. We used the 830 lines mm^{-1} grating with the order blocking filter OG550. The wavelength coverage is roughly from 6000 to $10,000\text{ \AA}$. With a $1''$ slit width, the resolving power was ~ 3600 . The total integration time per mask was ~ 3 hours, broken into individual exposures of 20 or 30 min. We also observed a spectrophotometric standard star BD+28d4211 in long-slit mode with the same grating and order blocking filter. The data were reduced with the DEEP2 DEIMOS data pipeline based on the `spec2d` IDL package⁹. The DEIMOS flexure compensation system (FCS) failed in the beginning of our observing run, which caused problems with the data reduction, as flexure could happen in both spatial and spectral directions.

⁹ The analysis pipeline used to reduce the DEIMOS data was developed at UC Berkeley with support from NSF grant AST-0071048.

We shifted the spectral images along the both directions manually based on sky emission lines and flat-field images before we fed the data to the pipeline. The pipeline corrected for any small residual shifts.

We extracted the spectra of our targets and flux-calibrated the spectra using alignment stars. There were typically 4–5 bright ($16 < R < 17$) alignment stars per mask used to align masks. They were put in 4'' square boxes rather than 1'' slits. The advantage of using alignment stars for flux calibration is that alignment stars and the targets were observed under exactly the same conditions such as transparency and airmass. For each mask, we first measured the spectral response from the spectra of standard star BD+28d4211, and extracted the spectra of the alignment stars. We then calculated the count-to-flux ($\text{erg s}^{-1} \text{cm}^{-2} \text{\AA}^{-1}$) ratios by scaling the spectra of the alignment stars to their broad-band photometry (i' or z'). The ratios among different alignment stars on a mask agree within 0.1 mag. We also incorporated slit loss (~ 0.24) into the count-to-flux conversion ratios. The slit loss was estimated by assuming a slit width of 1'' and a stable Gaussian PSF of 1'' (typical seeing). Finally the average of conversion ratios was applied to the spectra of other objects in this mask. Because the PSF is comparable to the slit width, the slit loss varies with varying seeing, possible offsets between targets and slits, and even the sizes of targets. We did not correct for these minor changes.

3. RESULTS

Among six mask images, one (the first one during which FCS failed) had more than twice lower slit throughput due to the failure of FCS or other unknown reasons. We identified one very bright LAE (out of 14 candidates) in this mask (No. 19 in Table 1 and Figures 1 and 2, see the following paragraphs), but we will not include this one in the analysis of spatial density and LF in the next section. In the other five masks, we identified 18 galaxies (out of 59 candidates) with prominent Ly α emission lines. Our 3σ detection limit is about $0.7 \times 10^{-17} \text{ erg s}^{-1} \text{cm}^{-2}$ at $\sim 8500 \text{ \AA}$, and is estimated as follows. The detection limit depends on the shape of the Ly α lines, as narrower lines (for a given flux) are easier to identify. Kashikawa et al. (2011) generated two composite Ly α emission lines for their $z \sim 5.7$ and 6.5 LAEs and found that the two lines were very similar. We create a Ly α emission model image with the shape of the composite $z \sim 6.5$ LAE profile. We then scale this model image and put a number of them onto the spectral images. The flux limit is determined by detecting these simulated Ly α emission from the spectral images. Briefly we found one galaxy out of 14 candidates in the mask with very low throughput and found 18 galaxies out of 59 candidates in the other five masks. The remaining candidates do not show any continuum emission nor line emission, so we were not able to identify them.

Figure 1 shows the thumbnail images of these galaxies in two broad bands i' and z' and one narrow band NB921. They were barely detected in the i' -band images and totally invisible in the BVR bands. Most of them were also barely detected in the NB921 band. Figure 2 shows the DEIMOS spectra and the redshifts of the 19 galaxies. The spectra have been flux calibrated and are placed on an absolute flux scale using alignment stars.

We can clearly see asymmetry in the emission lines of relatively bright galaxies. This is the indicator of the Ly α emission line at high redshift due to strong neutral intergalactic medium (IGM) absorption blueward of the line. The non-detection in deep BVR images implies that they are not likely low-redshift contaminants. In addition, the large wavelength coverage rules out the possibility that the detected lines are one of the H β , [O III] $\lambda 5007$, or H α lines. The high resolution of the spectra also ensures that they are not [O II] $\lambda 3727$ doublets. In a few cases in Figure 2 there are some residual sky lines redward of Ly α that appear like emission lines. They are not the AGN feature N V $\lambda 1240$, because at $z \sim 6$ the N V emission line is $\sim 170 \text{ \AA}$ away.

Table 1 lists the galaxy coordinates, redshifts, and z' -band magnitudes, as well as other properties that will be described below. This galaxy sample spans a redshift range $6 \leq z \leq 6.4$ and a magnitude range of $25.1 \leq z' \leq 27$. Redshift for each galaxy is measured from the Ly α line center using a Gaussian profile to fit the top $\sim 50\%$ of the line from the peak (the rest-frame Ly α line center is assumed to be 1216 \AA). Note that the no. 13 galaxy in our list is no. 2 in the photometric sample of Shimasaku et al. (2005).

We measure observed Ly α line fluxes by integrating the Ly α spectra over rest-frame $1215.2 (=1216-0.8)$ to $1217.2 (=1216+1.2) \text{ \AA}$. We do not correct for IGM absorption blueward of the line. Table 1 shows the flux measurements and the Ly α luminosities derived from the observed fluxes. Most of the galaxies in our sample have the Ly α fluxes in a range of $(0.7 \sim 2.4) \times 10^{-17} \text{ erg s}^{-1} \text{cm}^{-2}$, comparable to the Ly α fluxes in the SDF $z \sim 6.5$ LAE sample (Kashikawa et al. 2006). The strongest Ly α emission line ($5.8 \times 10^{-17} \text{ erg s}^{-1} \text{cm}^{-2}$) in our sample is as bright as the strongest LAEs from large LAE surveys of Ouchi et al. (2009), Hu et al. (2010), and Kashikawa et al. (2011), indicating that it represents the bright end of LAEs at $z > 6$. Table 1 also includes the star formation rates (SFRs) estimated from the Ly α luminosities by

$$\text{SFR}(\text{Ly}\alpha) = 9 \times 10^{-43} \text{ L}(\text{Ly}\alpha) \text{ M}_{\odot} \text{ yr}^{-1}, \quad (2)$$

which is based on the relation between SFR and the H α luminosity (Kennicutt 1998) and the line emission ratio of Ly α to H α in Case B recombination (Osterbock et al. 1989). The derived SFRs are less than $10 \text{ M}_{\odot} \text{ yr}^{-1}$ for all but one galaxy.

We estimate the Ly α rest-frame equivalent widths (EWs) using the observed Ly α fluxes and z' -band photometry. Although the narrow-band NB921 photometry consists of pure continuum flux for objects at $z < 6.5$, our galaxies are mostly very faint in this band, preventing us from measuring reliable photometry. The broad z' band includes emission from both continuum and Ly α . To decompose the z' -band photometry we assume that the UV continuum slopes ($f_{\lambda} \propto \lambda^{\beta}$) are $\beta = -2$ (Bouwens et al. 2009). We further assume that the continuum blueward of Ly α is entirely absorbed by IGM. This is reasonable as seen from $z \sim 6$ quasars (Fan et al. 2006). The only free parameter is then the continuum level when an observed spectrum (continuum+Ly α) is scaled to match the corresponding z' -band photometry. The results of the Ly α EWs are listed in Column 8 of Table 1. Column

6 shows M_{1300} , the absolute AB magnitude of continuum at rest-frame 1300 Å. The EW measurements are rough due to uncertainties from the broad-band photometry, Ly α fluxes, and UV slopes. We vary the assumed slope by 0.5 and the typical change on the measured EWs is smaller than 15%. For a few galaxies with strong NB921 detections, we also derive their EWs based on the continua from their NB921 photometry. The results mostly agree with the above measurements within 25%. Nevertheless, there is no doubt that most of the galaxies in our sample have large EWs. The median value of the EWs is 50 Å, with 4 galaxies having EWs higher than 100 Å. They are on average smaller than those in the bright sample of Nagao et al. (2004, 2005, 2007), whose Ly α EWs are in the range of 90–240 Å.

4. DISCUSSION

4.1. Spectral Properties

We know little about the Ly α EW distribution of LBGs at $z \sim 6$. Current facilities can only identify $z \sim 6$ LBGs with prominent Ly α lines, but it is known that most LBGs at low redshift do not have strong Ly α emission. At $z = 2 \sim 3$, the Ly α EW distribution has been well determined based on a spectroscopic sample of more than 1000 LBGs (Shapley et al. 2003; Reddy et al. 2008; Reddy & Steidel 2009). A half of the LBGs in this sample have Ly α absorption lines instead of emission lines, and only 17% have Ly α EWs greater than 30 Å (with $\sim 10\%$ having EWs > 50 Å), while almost all the LBGs in our sample have EWs > 30 Å. Therefore, LBGs in our $z > 6$ sample have much stronger Ly α emission on average. Statistics of Ly α EWs for LBGs at $z > 5$ has been tentatively investigated (e.g. Stark et al. 2010, 2011). For example, Stark et al. (2011) found that at $-21.75 < M_{UV} < -20.25$ the fractions of LBGs with EWs > 25 and > 55 Å are roughly 20% and 8%, respectively, and at $-20.25 < M_{UV} < -18.75$ the two fractions increase rapidly to $\sim 55\%$ and $\sim 25\%$. Our sample spans a UV luminosity range of $-21.8 \leq M_{1300} \leq -19.5$, and the two fractions in our sample are 25% (15/59) and 14% (8/59), broadly consistent with the trend shown in their results.

The Ly α strength may also vary with luminosity. Some studies have reported the inverse relationship between Ly α EW and UV luminosity (e.g. Shapley et al. 2003; Ando et al. 2006; Reddy et al. 2008; Stark et al. 2010), while others claimed that the relation is not obvious or there is no such relation (e.g. Nilsson et al. 2009). Figure 3 shows the Ly α EW as a function of the continuum luminosity M_{1300} for our sample. The dashed line demonstrates the detection limit for galaxies at $z = 6.2$. The apparent strong correlation between EW and M_{1300} in our sample is likely due to the nature of flux-limited surveys. Nevertheless, our sample has a similar luminosity range as the range of the $z \sim 3$ LBG sample mentioned above. In the next section we will use the EW distribution at $z \sim 3$ (Reddy & Steidel 2009) to correct for sample incompleteness.

4.2. Sample Completeness

The galaxies presented in this paper provide a well-defined flux-limited galaxy sample down to $z' = 27$. The

effective area is ~ 340 arcmin² (five DEIMOS mask coverage) and the redshift range is $6 \leq z \leq 6.4$. In the following subsections we will correct for sample incompleteness, calculate the spatial density of the galaxies, and derive the galaxy LF in this redshift range.

Due to various selection criteria that we applied, our sample is incomplete. The sample completeness is complicated. Here we correct for incompleteness which originates from three major steps, source detection, galaxy candidate selection, and spectroscopic identification. The first major incompleteness comes from the detection of sources in the SDF image. Because the SDF field is crowded, any high-redshift galaxies behind foreground objects are not detected. It is straightforward to calculate this incompleteness by measuring the fraction of the area occupied by bright objects. There is another source of incompleteness due to the fact that fainter objects are more difficult to detect. We put a large number of simulated galaxies (point sources) in the SDF z' -band image and detect them using **SExtractor** (Bertin & Arnouts 1996) in the way used for our galaxy candidate detection. We then measure the completeness as a function of magnitude z' by counting the fraction of detections. The combined completeness is about 75% at $z' < 25$ and drops to $\sim 65\%$ at $z' = 27$.

The second major incompleteness comes from the magnitude limit ($z' < 27$) and color cut ($i' - z' > 1.7$) that we applied to the candidate selection. The last major incompleteness is from the fact that our sample is biased towards LBGs with strong Ly α emission, as discussed above. We cannot identify LBGs with Ly α fluxes below our detection limit in the DEIMOS spectra. We use a selection function to correct these incompletenesses.

The selection function is defined as the probability that a galaxy with a given magnitude, redshift, and intrinsic spectral energy distribution (SED) meets the criteria of our candidate selection and Ly α identification. By assuming a distribution for the intrinsic SEDs, we calculate the average selection probability as a function of magnitude and redshift. To do this, we first produce a large set of galaxy spectra for a given (M_{1300}, z), using the Bruzual & Charlot (2003) stellar population synthesis model with the Salpeter IMF. The magnitude M_{1300} is the absolute AB magnitude at rest-frame 1300 Å, and 1300 Å is chosen to be close to the z' -band effective wavelength for $z \sim 6$ galaxies. The input model parameters will be described in detail in the next paragraph. We then apply IGM absorption to the model spectra. The neutral IGM fraction increases dramatically from $z = 5.5$ to $z = 6.5$, causing complete Gunn-Peterson troughs in some $z > 6$ quasar spectra (Fan et al. 2006). It is thus critical to predict $i' - z'$ colors. We calculate IGM absorption in the way used by Fan et al. (2001) and Jiang et al. (2008). Finally we measure the apparent magnitudes from the model spectra with the SDF filter transmission curves. We also incorporate photometric errors into each band. It is particularly important for faint objects, as a non-negligible fraction of real galaxies may have been scattered out of the selection region due to large photometric errors. The selection probability for this galaxy (M_{1300}, z) is then the fraction of model galaxies that meet all our criteria.

The intrinsic SEDs of galaxies depend on their physical

properties such as age, metallicity, and dust extinction. However, we know very little about physical properties of $z > 6$ galaxies. We determine input parameters for the above synthesis models from our *HST* and *Spitzer* observations of 20 spectroscopically-confirmed LAEs and LBGs at $5.6 < z < 7$ in SDF (E. Egami et al., in preparation). This sample is bright, and the spectroscopic redshifts remove one critical free parameter for SED modeling. The *HST* near-IR data provides rest-frame UV photometry to decipher the properties of young stellar populations, while the *Spitzer* IRAC data measure the amplitude of the Balmer break and constrain the properties of mature populations. We find that there is a wide variety of SEDs among these galaxies, such as mature galaxies with ages > 100 Myr and young galaxies with ages ~ 1 Myr. The dust extinction is low to moderate, consistent with the general trend that higher-redshift galaxies have bluer UV continuum slope and lower dust extinction (Bouwens et al. 2009). Based on these results, our model parameters are set as follows. At a given redshift (from 5.5 to 7.2), we choose to use a mixed grid of six ages [1, 2, 5, 10, 40, 100] Myr and three dust extinction values $E(B-V) = [0.02, 0.1, 0.3]$. The metallicity for the models with ages of 1 and 2 Myr is $0.005 Z_{\odot}$, for the models of with ages of 5 and 10 Myr is $0.02 Z_{\odot}$, and for the models of with ages of 40 and 100 Myr is $0.2 Z_{\odot}$. The selection function is not sensitive to these physical parameters such as age, metallicity, and dust extinction. After we generate the galaxy continuum spectra using the Bruzual & Charlot (2003) model, we add Ly α emission lines to the spectra. The Ly α emission in our galaxies is strong, and has significant contribution (~ 0.4 mag) to the z' -band photometry. As we discussed in Section 3, we know very little about the statistics of Ly α strengths at $z \sim 6$. Therefore we assume that the rest-frame EWs of Ly α at $z \sim 6$ have a distribution similar to that of $z \sim 3$ (Reddy & Steidel 2009).

Figure 4 shows the selection function as a function of M_{1300} and z . The contours in the figure are selection probabilities from 5% to 35% with an interval of 5%. The sharp decrease of the probability at $z \sim 6$ is due to the color cut of $i' - z' > 1.7$. The solid circles are the locations of the 19 $z > 6$ galaxies in our sample. Figure 4 does not include two small constant incompletenesses. One is from slit conflict during DEIMOS slit assignment; $\sim 8\%$ candidates were not allocated slits. The other one is due to the existence of strong sky OH lines; emission lines that happen to be on these OH lines are much more difficult to identify. Although in principle this incompleteness is also a function of magnitude and redshift, we find that 5% is a good approximation for our sample in the range of 8500–9000 Å (e.g. Stark et al. 2010). Figure 4 does not take into account the rejection of $z \sim 6.5$ LAEs either, otherwise there will be a ‘dip’ at $z \sim 6.5$ in the selection function of Figure 4.

4.3. UV Luminosity Function

We derive the volume density of the galaxies at $z > 6$ using the traditional $1/V_a$ method. The available volume for a galaxy with absolute magnitude M_{1300} and redshift z in a magnitude bin ΔM and a redshift bin Δz is

$$V_a = \int_{\Delta M} \int_{\Delta z} p(M_{1300}, z) \frac{dV}{dz} dz dM, \quad (3)$$

where $p(M_{1300}, z)$ is the probability function used to correct for all the sample incompletenesses described above. Then the spatial density and its statistical uncertainty can be written as (Page & Carrera 2000)

$$\rho = \frac{N_{gal}}{V_a}, \quad \sigma(\rho) = \frac{N_{gal}^{1/2}}{V_a}, \quad (4)$$

where N_{gal} is the number of galaxies in the bin $(\Delta M, \Delta z)$. The magnitude and redshift distributions of the galaxies in our sample are shown in Figure 4. We measure galaxy densities in one redshift bin $5.8 < z < 6.5$ and three magnitude bins $[-19.4, -20.4]$, $[-20.4, -21.4]$, and $[-21.4, -23]$. The lower limits of redshift and magnitude are chosen to be our detection limit (probability in Figure 4 below 5%). The magnitude upper limit -23 of the last bin is an assumption, comparable to the brightest LBG candidates in the largest LBG sample of McLure et al. (2009). We choose 6.5 as our upper limit of redshift because we were not able to identify LBG candidates at $z > 6.6$ (see subsection 4.5 for discuss) and the LAEs at $z \sim 6.56$ are being targeting in another program (see Section 2).

Figure 5 shows our measurements of the spatial densities (the filled circles with error bars) in the three magnitude bins at $\langle z \rangle \sim 6.2$. It also compares with the UV LFs at $z = 5, 5.9$, and 6.8 from other studies (Bouwens et al. 2007; McLure et al. 2009; Ouchi et al. 2009; Bouwens et al. 2011). Bouwens et al. (2007) obtained a large sample of LBG candidates from the HUDF and other *HST* datasets. They derived the UV LFs at $z = 5$ and 5.9 (the blue and green dashed lines in Figure 5) down to a depth of $M_{UV} \sim -17$ and -18 , respectively, and found very steep faint-end slopes ($\alpha \sim -1.7$) at these redshifts. McLure et al. (2009) extended the *HST* sample by including brighter LBG candidates selected from the UKIDSS Ultra Deep Survey (UDS). They found very similar LFs at $z \sim 5$ and 6 (the blue and green dotted lines in Figure 4). The $z = 6.8$ LFs in Figure 5 were measured with the data from the new *HST* WFC3 IR camera (Bouwens et al. 2011) and with the deep SDF Y-band imaging data (Ouchi et al. 2009). It is clear that our spectroscopic result is in good agreement with the trend of the LFs from $z = 5.9$ to 6.8 from the previous studies. Note that k-correction within a small UV wavelength range (1300 \sim 1600 Å) is negligible because of the blue UV slopes.

We parametrize the galaxy UV LF at $z \sim 6$ from our spectroscopic sample using a Schechter function,

$$\phi(M) = 0.4 \ln 10 \phi^* 10^{-0.4(M-M^*)(\alpha+1)} \exp(-10^{-0.4(M-M^*)}), \quad (5)$$

where ϕ^* is the normalization, M^* is the characteristic luminosity, and α is the faint-end slope. Because our sample is not deep enough to well determine α , and the measurements of α at $5 \leq z \leq 6$ from previous studies are quite robust and consistent, we fix α to the value of -1.74 given by Bouwens et al. (2007). We then fit our data to the above function. The best fits are $\phi^* = (1.7 \pm 1.2) \times 10^{-3} \text{ Mpc}^{-3}$ and $M^* = -19.97 \pm 0.32$, consistent with the result of Bouwens et al. (2007) ($\phi^* = 1.4 \times 10^{-3} \text{ Mpc}^{-3}$ and $M^* = -20.24$) and the result of McLure et al. (2009) ($\phi^* = 1.8 \times 10^{-3} \text{ Mpc}^{-3}$ and $M^* = -20.04$) at $z \sim 6$. The best-fitting $M^* = -19.97$ indicates that our sample

spans a large luminosity range $0.6 L^* \sim 5 L^*$ across the characteristic luminosity L^* at $z \sim 6.2$. The result is shown in Figure 5.

Cosmic variance has a minor effect on our results. The six masks covered different parts of SDF, and we did not exclusively target denser regions of the LBGs candidates. We covered 79 candidates in 340 arcmin^2 , while we selected 196 promising candidates in the whole SDF field ($\sim 876 \text{ arcmin}^2$). The candidate surface density in the six masks ($0.23 = 79/340$) is close to the average density of the field ($0.22 = 196/876$). Therefore our sample is a representative sample of SDF. We calculate the uncertainty originating from cosmic variance for all the SDF candidates using the Trenti & Stiavelli (2008) calculator. Within a redshift range of $5.8 < z < 6.5$ the uncertainty is only $\sim 20 \%$, much smaller than statistical errors in ϕ^* and M^* .

Our galaxy sample is a well-defined spectroscopic sample of LBGs at $z > 6$. The comparison in Figure 5 shows that our measurement of the UV LF at $z \sim 6$ are consistent with the results from deep *HST* and UKIDSS observations. However, our LF largely depends on the selection function described in Figure 4. Our tests show that the selection function is not sensitive to the physical parameters such as age, metallicity, and dust extinction, but is sensitive to the distribution of Ly α EWs. Because the fraction of strong LAEs among LBGs is small, we have applied a large correction in the selection function. Figure 5 may indicate that the distribution of Ly α strength at $z \sim 6$ is similar to that at $z \sim 3$. Otherwise our LF will be quite different from the previous measurements of the $z \sim 6$ LFs. Alternatively, the contamination rates in previous LBG samples should be small. For example, the contamination rate in the Bouwens et al. (2007) sample was claimed to be as small as $\sim 3 \%$, and in the Bouwens et al. (2011) sample was found to be less than 14% . If their contamination rates are higher, the number densities derived from their samples will be lower, in contrary to Figure 5.

4.4. Ly α Luminosity Function

We also derive the Ly α LF using the way very similar to what we do for the UV LF. The Ly α luminosities $L(\text{Ly}\alpha)$ are listed in Table 1. We first calculate the selection function to correct for incompleteness for our galaxies as a sample of LAEs. Simulated galaxies are generated using the Bruzual & Charlot (2003) synthesis model as described in Section 4.2. The only difference is the assumption of the Ly α EW distribution. The statistics of Ly α strengths in LAEs at $z \sim 6$ has been determined in several studies. We use the EW probability distribution estimated from a sample of photometrically selected LAEs of Ouchi et al. (2008). Figure 6 shows the LAE selection function as a function of $L(\text{Ly}\alpha)$ and z . The contours in the figure are selection probabilities from 10% to 70% with an interval of 10%. The selection function is generally similar to the one for LBGs in Figure 4, except that the selection probabilities for LAEs are more than three times higher than those for LBGs. This is because for LAEs we do not need to apply a large correction due to the small fraction LAEs among LBGs.

The volume densities of the LAEs are computed in four luminosity ($\log L$) bins $[42.35, 42.60]$, $[42.60, 42.85]$, $[42.85, 43.10]$, and $[43.10, 43.50]$. The lower limit 42.35

of the first bin is chosen to be our detection limit (probability in Figure 6 below 5%). The brightest bin contains only one galaxy and the bin size is arbitrary, so we do not include this bin in the following analysis. We estimate the Ly α LF using a Schechter function,

$$\phi(\log L) = \ln 10 \phi^* (L/L^*)^{\alpha+1} \exp(-L/L^*). \quad (6)$$

Most galaxies in our sample cover the faint end of the Ly α LF, so we are not able to well determine L^* . Therefore we fix $\log L^*$ to be the value of 43.0 (e.g. Kashikawa et al. 2006; Hu et al. 2010; Cassata et al. 2011; Kashikawa et al. 2011) when we fit our data to the above function. The best fits are $\phi^* = (8.2 \pm 3.3) \times 10^{-5} \text{ Mpc}^{-3}$ and $\alpha = -1.67 \pm 0.54$. Figure 7 shows our measurements of the densities (filled circles with error bars) and the best model fit (solid curve). As we mentioned, the selection function is sensitive to the Ly α EW distribution, especially in the faint end of the sample. The filled triangles in Figure 7 represent the volume densities if the assumed EW distribution is increased by 30 \AA (to roughly match the EW distribution for the spectroscopic sample shown in Ouchi et al. (2008)). The density in the faintest bin is increased by a factor of two. In Figure 7 we also show the comparison with the Ly α LF measurements at $z \sim 6.5$ from Hu et al. (2010), Kashikawa et al. (2011), and Ouchi et al. (2010). The results of Kashikawa et al. (2011) and Ouchi et al. (2010) agree with each other in a wide luminosity range covered. The result of Hu et al. (2010) also agrees with them in the bright end of the LF, but show a significant discrepancy in the faint end, where the density of Hu et al. (2010) is about three times lower. The reason is still unclear. Our LF in the faint end is slightly higher than that of Hu et al. (2010), but is lower than the Kashikawa et al. (2011) and Ouchi et al. (2010) LFs. Given the large uncertainties our result is generally in agreement with these previous LAE surveys.

4.5. Did We Miss $z > 6.6$ LBGs?

The most distant galaxy in our sample is at $z \sim 6.4$, and we did not find any galaxies at $z > 6.6$. The reason is complicated. The deep z' -band image used in this paper has securely detected one of the most distant LAEs known at $z = 6.96$ (Iye et al. 2006). We successfully recovered this object during our candidate selection, and we also have six good $z > 6.6$ candidates that have been observed. If they were galaxies like the $z = 6.96$ LAE, we should have identified them in the DEIMOS mask images. This is illustrated in Figures 4 and 6. The detection probability of the $z = 6.96$ LAE is higher than those for a half of the LBGs or LAEs in our sample. However, the throughput of DEIMOS drops steadily from 9000 \AA towards higher wavelength, and in this range the sky background is brighter and the OH lines are denser. These issues result in significantly lower signal-to-noise ratios in the DEIMOS images, but they were not considered in Figures 4 and 6. Therefore it is likely that our spectra at $> 9000 \text{ \AA}$ are not deep enough to identify Ly α emission lines. On the other hand, we cannot rule out the possibility that there are no $z > 6.6$ LBGs with strong Ly α emission in the covered region. Due to the increasing neutral fraction of IGM at $z > 6$, the density of LAEs at the bright end may decline rapidly towards higher red-

shifts (e.g. Kashikawa et al. 2011; Pentericci et al. 2011; Schenker et al. 2011).

5. SUMMARY

In this paper we have reported the discovery of 19 LBGs from our deep spectroscopic observations of a sample of $z > 6$ LBG candidates in SDF. The candidates were selected using the traditional dropout technique from an ultra-deep z' -band image. This image, with a total integration time of 29 hours, enables us to select galaxies down to $z' = 27$ mag over a wide field. The follow-up spectroscopy was made with Keck DEIMOS. The 19 LBGs span a redshift range of $6 \leq z \leq 6.4$ and a magnitude range of $25.1 \leq z' \leq 27$. They have moderate Ly α emission line strengths compared to those in LAEs at similar redshifts. The median value of rest-frame Ly α EWs is ~ 50 Å, and four LBGs have EWs > 100 Å.

This well-defined spectroscopic LBG sample spans a UV luminosity range of $0.6 \sim 5 L_{\text{UV}}^*$ across the UV characteristic luminosity L_{UV}^* and a Ly α luminosity range of $0.3 \sim 3 L_{\text{Ly}\alpha}^*$ across the Ly α characteristic luminosity $L_{\text{Ly}\alpha}^*$. It thus provides unique constraints on both the UV and Ly α LFs at $z > 6$. We correct for sample incompleteness from source detection, galaxy candidate selection, and spectroscopic identification. In particular, for the UV LF we assume that the distribution of Ly α EWs at $z \sim 6$ is the same as that at $z \sim 3$. We then

calculate the volume density of the galaxies and estimate the LFs at $\langle z \rangle \sim 6.2$ using a Schechter function. We find that our measurement of the UV LF is consistent with the results of previous studies based on photometric LBG samples at $5 < z < 7$, including samples from HDF and UKIDSS UDF. Our Ly α LF is also in agreement with the results of Ly α -emitter surveys at $z \sim 5.7$ and 6.6.

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TABLE 1
PROPERTIES OF THE 19 LBGs

No.	RA (2000)	Dec (2000)	Redshift	z' (mag)	M_{1300} (mag)	$f(\text{Ly}\alpha)$ (10^{-17} erg s $^{-1}$ cm $^{-2}$)	EW(Ly α) (Å)	$L(\text{Ly}\alpha)$ (10^{42} erg s $^{-1}$)	SFR(Ly α) (M_{\odot} yr $^{-1}$)
1	13:25:18.142	27:32:32.449	6.240	26.99	−19.80	0.8	47	3.5	3.2
2	13:24:55.589	27:39:20.772	6.125	26.69	−19.63	1.4	90	5.7	5.2
3	13:24:41.333	27:43:16.601	6.394	26.47	−20.69	1.3	35	5.9	5.4
4	13:24:36.893	27:43:41.520	6.343	26.38	−20.74	1.2	29	5.2	4.7
5	13:25:11.086	27:37:47.957	6.146	26.29	−20.51	1.0	23	3.4	3.1
6	13:24:26.030	27:16:02.993	5.992	26.88	−19.54	1.2	81	4.7	4.3
7	13:24:20.626	27:16:40.408	6.267	26.91	−19.90	1.0	50	4.1	3.7
8	13:24:05.894	27:18:37.703	6.047	26.82	−19.74	0.7	41	2.8	2.6
9	13:24:10.769	27:19:03.918	6.038	26.61	−19.57	1.7	120	7.2	6.5
10	13:24:34.824	27:14:18.985	6.233	26.98	−19.67	1.1	63	4.1	3.8
11	13:25:21.053	27:15:24.023	6.076	26.34	−19.95	1.9	92	7.8	7.1
12	13:25:22.190	27:21:41.069	6.214	26.56	−19.51	2.4	170	9.6	8.7
13	13:25:27.804	27:28:58.742	6.226	25.31	−21.77	1.1	10	4.6	4.2
14	13:23:38.616	27:26:15.623	6.051	26.73	−19.83	0.7	41	3.1	2.8
15	13:23:45.758	27:32:51.342	6.313	25.59	−21.66	0.9	10	4.2	3.8
16	13:23:42.137	27:33:33.905	6.038	26.05	−20.58	1.1	30	4.5	4.1
17	13:23:50.484	27:34:15.078	6.302	26.72	−19.80	1.6	101	7.5	6.8
18	13:24:26.107	27:18:40.450	6.131	26.59	−19.52	2.0	136	7.7	7.0
19	13:25:21.612	27:42:28.915	6.164	25.10	−21.25	5.8	95	26.5	24.1

NOTE. — The magnitude M_{1300} is the absolute AB magnitude of continuum at rest-frame 1300 Å. EW(Ly α) is the Ly α rest-frame equivalent width. The Ly α properties are not corrected for IGM absorption.

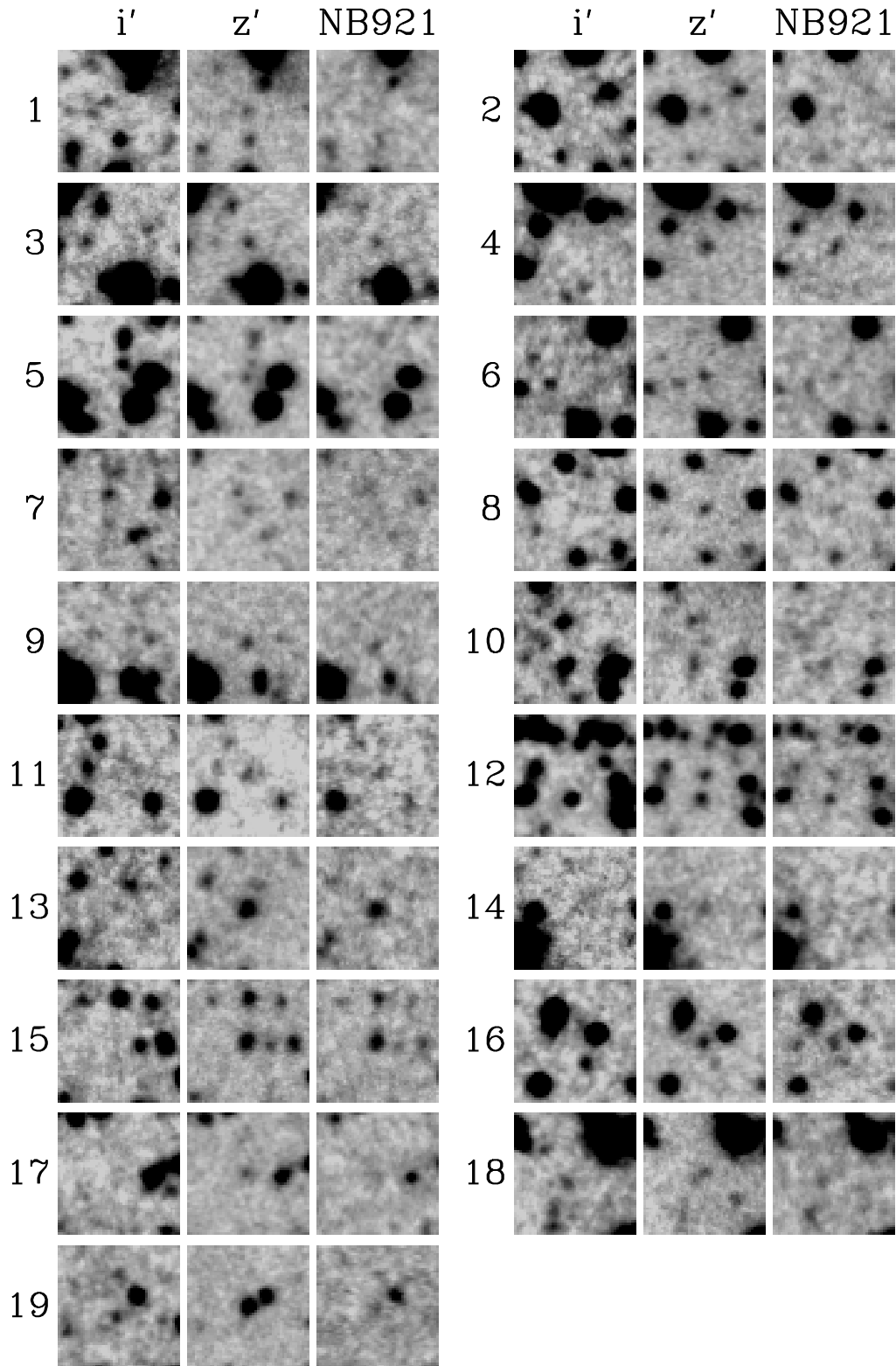


FIG. 1.— Thumbnail images of the 19 LBGs in two broad bands i' and z' and one narrow band NB921. The image size is $10'' \times 10''$. North is up and east to the left. These galaxies were barely detected in the i' -band images and totally disappeared in the BVR bands. Most of them were also barely detected in the NB921 band.

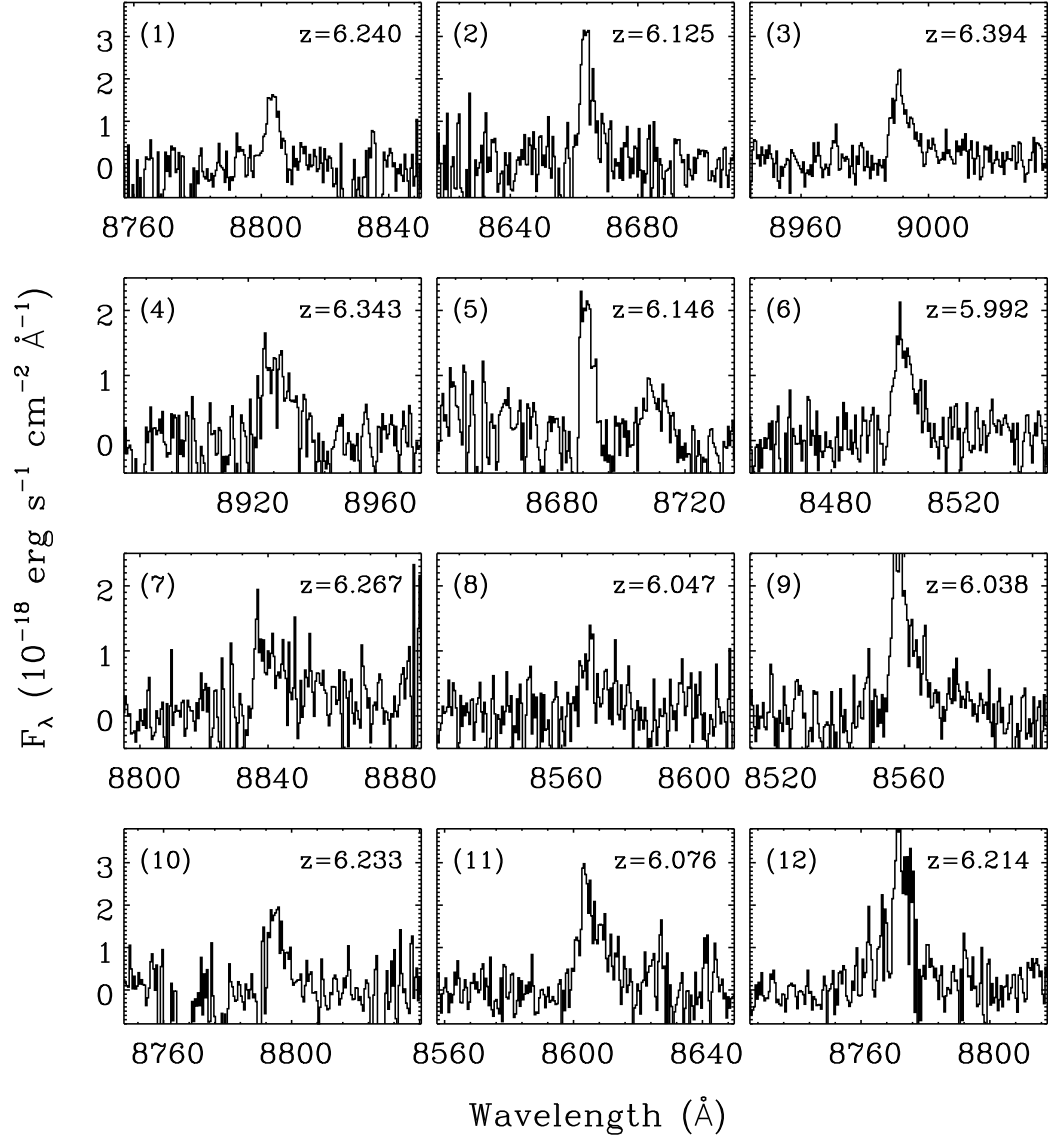


FIG. 2.— Spectra of the 19 LBGs. The Ly α emission line is shown in the center of each panel. The spectra have been flux calibrated and are placed on the absolute flux scale.

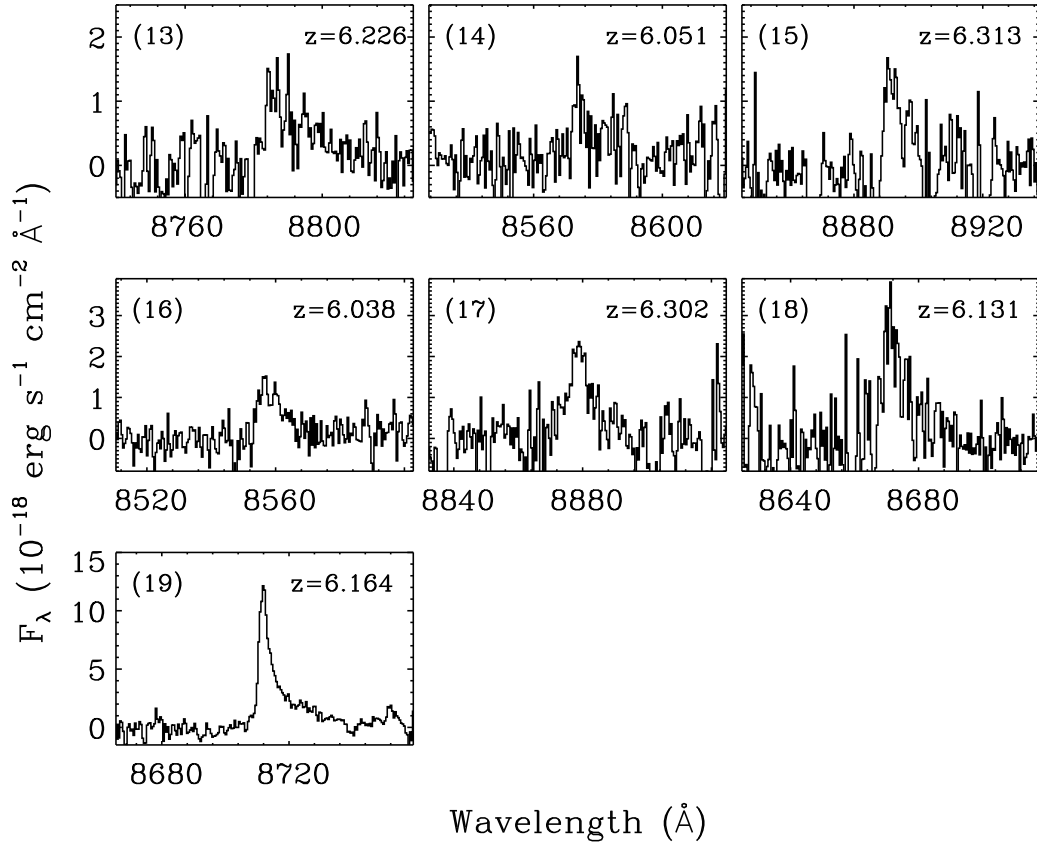


FIG. 2.— Continued.

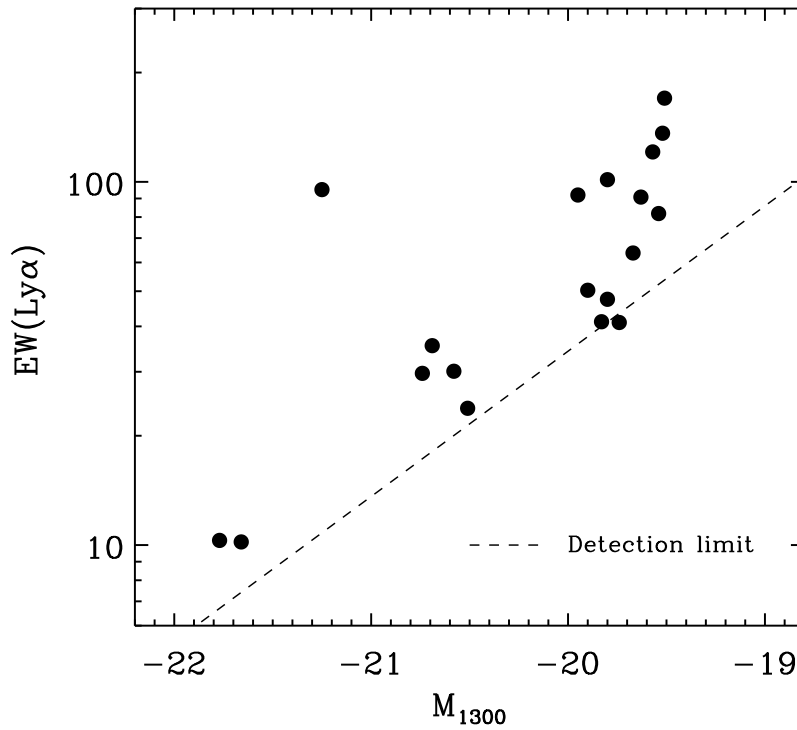


FIG. 3.— Ly α EW as a function of the continuum luminosity M_{1300} for our sample. The filled circles represent the 19 galaxies at $6 < z < 6.4$. The dashed line demonstrates our detection limit for galaxies at $z = 6.2$. The strong relation between EW and M_{1300} in our sample is very likely due to the nature of flux-limited surveys.

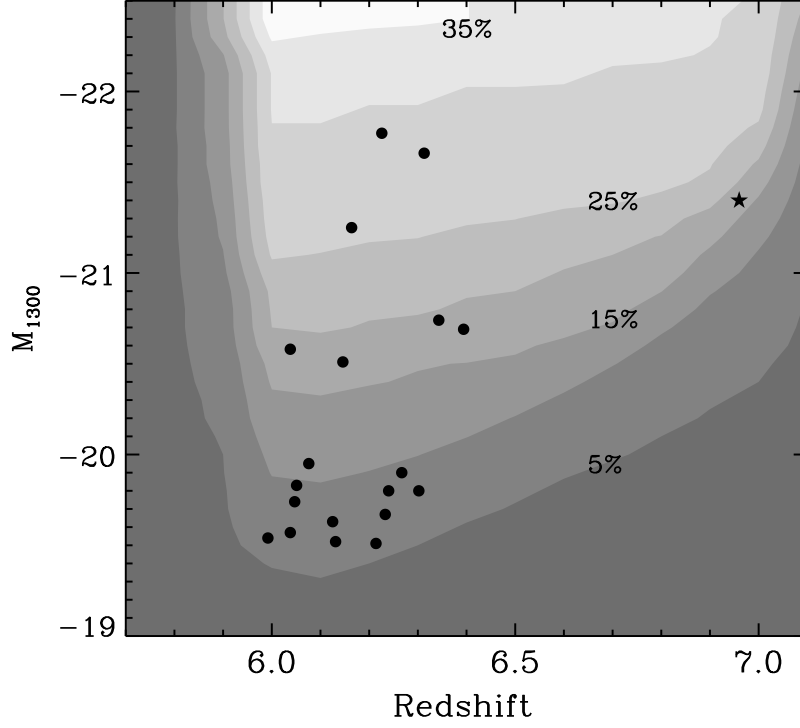


FIG. 4.— LBG selection function as a function of M_{1300} and z . The contours are selection probabilities from 5% to 35% with an interval of 5%. The filled circles are the locations of the 19 $z > 6$ galaxies in our sample. The filled star is the $z = 6.96$ LAE (Iye et al. 2006).

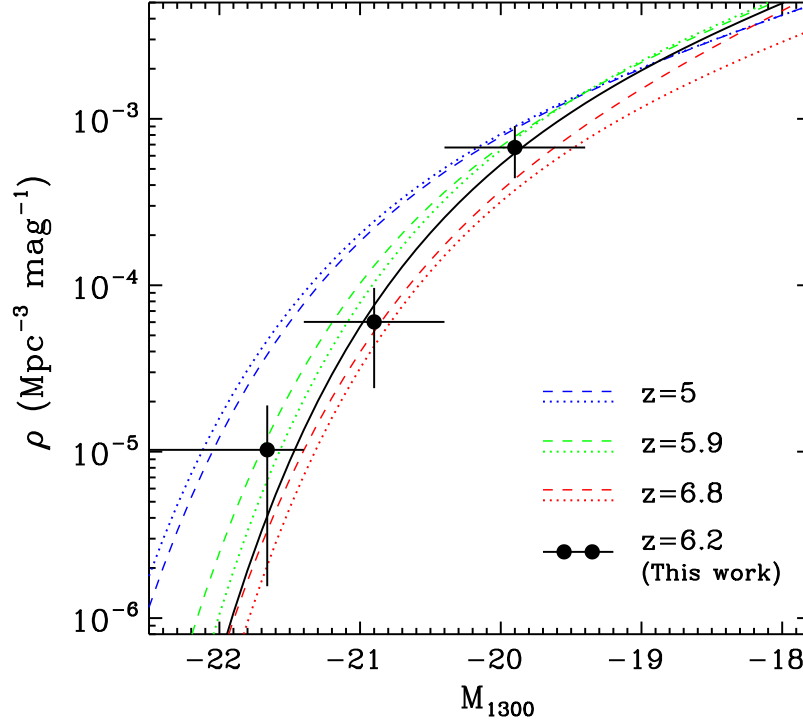


FIG. 5.— UV LF of LBGs at high redshift. The three filled circles are the spatial densities measured from our sample, and the solid curve is the best fit to a Schechter function. As comparison, color-coded dashed and dotted lines represent UV LFs from previous studies based on photometric LBG samples. The blue and green dashed lines: Bouwens et al. (2007). The blue and green dotted lines: McLure et al. (2009). The red dashed line: Bouwens et al. (2011). The red dotted line: Ouchi et al. (2009).

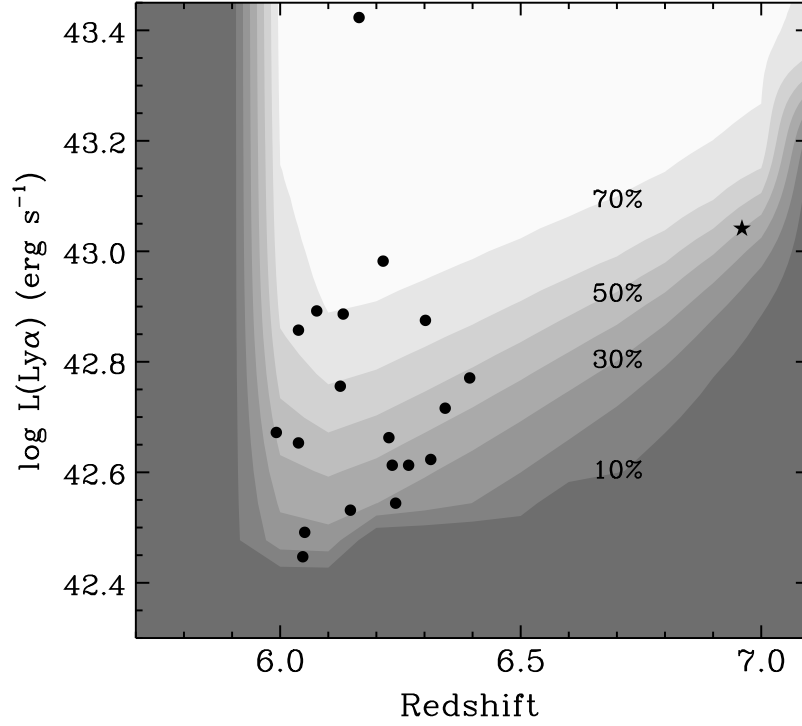


FIG. 6.— LAE selection function as a function of $L(\text{Ly}\alpha)$ and z . The contours are selection probabilities from 10% to 70% with an interval of 10%. The filled circles are the locations of the 19 $z > 6$ galaxies in our sample. The filled star is the $z = 6.96$ LAE (Iye et al. 2006).

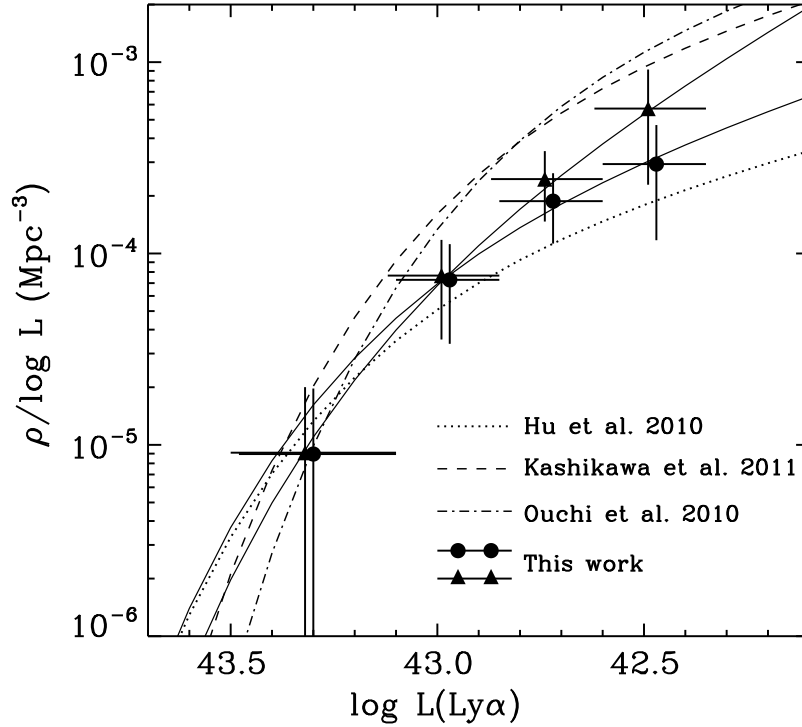


FIG. 7.— $\text{Ly}\alpha$ LF at high redshift. The filled circles and triangles are the spatial densities of our sample at $z \sim 6.2$ for two different $\text{Ly}\alpha$ EW distributions (see Sections 4.3 and 4.4). For the purpose of clarity, the triangles have been shifted 0.02 mag along the horizontal axis. The solid curves are the best fits to a Schechter function. The dotted, dashed, and dash-dotted lines represent the $\text{Ly}\alpha$ LFs of LAEs at $z \sim 6.5$ from Hu et al. (2010), Kashikawa et al. (2011), and Ouchi et al. (2010), respectively.